UNIVERSAL DESIGN RULES FROM PRODUCT PAIRS

AND ASSOCIATION RULE-BASED LEARNING

A Thesis

by

NICHOLAS COWEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Daniel A. McAdams
Committee Members,	Christian J. Schwartz
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ABSTRACT

Universal Design Rules From Product Pairs

and Association Rule-Based Learning. (May 2010)

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Chair of Advisory Committee: Dr. Daniel A. McAdams

A product pair is two products with similar functionality that satisfy the same high level need but are different by design. The goal of this research is to apply association rule-based learning to product pairs and develop universal design rules to be used during the conceptual design phase. The Apriori algorithm produced 1,023 association rules with input parameters of 70% minimum confidence and 0.5% minimum support levels. These rules were down-selected based on the prescribed rule format of: (Function, Typical User Activity) → (Change, Universal User Activity). In other words, for a given product function and user activity, the rules suggest a design change and new user activity for a more universal product.

This research presents 29 universal design rules to be used during the conceptual design stage. These universal design rules suggest a parametric, morphological, functional, or no design change is needed for a given user activity and product function. No design change rules confirm our intuition and also prevent inefficient design efforts. A parametric design change is suggested for actionfunction elements involving find hand use to manipulate a product. Morphological design changes are proposed to solve

actionfunction elements in a slightly more complex manner without adding or subtracting overall functionality. For example, converting human energy to mechanical energy with the upper body opposed to the lower body or actuating fluid flow with motion sensors instead of manual knobs. The majority of the recommended functional changes involve automating a product to make it more universal which might not be apparently obvious to designers during conceptual design.

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1. INTRODUCTION

In the United States, it is estimated that the percentage of people age 65 and over will increase from 12.4% in 2000 to 20.7% by 2050, whereas the percentage of people between the ages of 5 and 64 will decline from 80.7% to 72.7% by 2050 [1]. These statistics imply Americans are living longer. This longevity is largely due to healthier living and better medicine. In addition, more Americans are now living with disability. Of the 291.1 million people in the United States population in 2005, 54.4 million or 18.7% had some level of disability [2].

These demographics prove that our population is older and more disabled than many realize and these trends are on the rise. While human factors engineering has applied knowledge of human capabilities and limitations to the design of products, processes, systems, and environments, only a fraction of this work considers the needs of alternative users. Universal design is a concept intended to promote the development of products and environments to be used effectively by all users without adaptation or stigmatization.

If universal design has the ability to expand product use, why are companies not implementing this practice to increase production and sales? The answer involves several barriers to the adoption and successful practice of universal design by consumer product manufacturers revealed by a three-year study of small and large firms [3]. Some of the key barriers include concern that adopting universal design would require costly

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This thesis follows the style of Journal of Mechanical Design.

retooling and retraining of design teams, lack of knowledge within the company to practice universal design, and an informal or decentralized product development process which makes dissemination of universal design throughout the company difficult.

Although universal design may seem vague and burdensome, its application has broadened considerably since its origination in architecture. Universal design has grown to include the fields of product design, computers, electronics, telecommunication systems, and more [3]. The goal of this research is to apply association rule-based learning to product pairs and develop universal design rules to be used during the conceptual design phase. According to Beecher and Paquet [4], there exists a need for instruments that product developers can use to ensure their product can be used effectively by the widest range of potential user groups before it is mass produced.

This paper focuses on the study of fourteen typical and universal product pairs and the differences between actionfunction diagrams. Association rule-based learning, a data mining method, is applied to these product pairs to extract interesting relations and suggest how typical products can be made more universal.

The remainder of this paper is organized as follows. Section 2 covers the background of topics fundamental to this research including universal design, functional modeling with the Functional Basis, actionfunction diagrams with International Classification of Functioning (ICF) terminology, association rules, and the Apriori algorithm. Section 3 describes previous research and literature related to this research. The approach and methodology of this research is explained in Section 4, covering the product pair study and the generation and selection of the association rules. Section 5 describes the results of applying association rule-based learning to the product pair study. Section 6 illustrates rule application to unstudied consumer products. A conclusion and future work are presented in Section 7.

2. BACKGROUND

This research requires knowledge in several different fields of study. A background of universal design, the Functional Basis, functional modeling, ICF terminology, actionfunction diagrams, association rules, and the Apriori algorithm will be covered in the following sections.

2.1 Universal Design

Universal design has its beginnings in demographic, legislative, economic, and social changes among older adults and people with disabilities throughout the 20th century [5]. The term universal design was created in the early 1970's by Robert Mace, the founder of the Center for Universal Design at North Carolina State University, who defines universal design as the design of products and environments to be usable to the greatest extent possible by people of all ages and abilities [6].

Progress towards universal design gained public attention during the last few decades from three concurrent events including legislation stimulated by the disability rights movement, the barrier-free design to universal design movement, and developments in rehabilitation engineering and assistive technology. Influenced by the subsequent Disability Rights Movement of the Civil Rights Movement of the 1960's, current legislation prohibits discrimination against people with disabilities and provides them access to public amenities including education and transportation. Significant federal legislation leading to today's universal standards include The Architectural Barriers Act of 1968, Section 504 of the Rehabilitation Act of 1973, The Education for Handicapped Children Act of 1975, The Fair Housing Amendments Act of 1988, The

Americans with Disabilities Act of 1990, and The Telecommunications Act of 1996. The movement from barrier-free design to universal design has also lessened the stigmatization of people living with disabilities. While trying to incorporate standards into architecture, designers realized segregated accessible features were usually unattractive and costly. Understanding that accommodations made for people with disabilities in fact benefitted all people, designers recognized that accessible features could be commonly provided making them cheaper, attractive, and less stigmatized by lifting the "handicap" association.

Researchers at the Center for Universal Design at North Carolina State University compiled seven principles to guide designers when developing universal products and environments [7]. The seven principles of universal design are: 1) Equitable Use 2) Flexibility in Use 3) Simple and Intuitive Use 4) Perceptible Information 5) Tolerance for Error 6) Low Physical Effort and 7) Size and Space for Approach and Use. Each of these principles has a definition and guidelines, a list of the key elements that should be present in a design that adheres to the principle, which we will now take a closer look at.

Principle one, Equitable Use, is defined as "the design is useful and marketable to people with diverse abilities." There are four guidelines to this principle including: 1a) Provide the same means of use for all users: identical whenever possible; equivalent when not 1b) Avoid segregating or stigmatizing any users 1c) Make provisions for privacy, security, and safety equally available to all users and 1d) Make the design appealing to all users. For example, side-by-side refrigerators provide equitable use to users of all heights as shown in Fig. 1.

Fig. 1 The door handles on side-by-side refrigerators provide equitable use to users of all heights [a]

Principle two, Flexibility in Use, is defined as “the design accommodates a wide range of individual preferences and abilities.” There are four guidelines to this principle including: 2a) Provide choice in methods of use 2b) Accommodate right- or left-handed access and use 2c) Facilitate the user’s accuracy and precision and 2d) Provide adaptability to the user’s pace. Walkways with railings on both sides provide flexibility in use for right- and left-handed users as shown in Fig. 2.

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[a] Brownstoner.com, 2009, "Moving a Refrigerator," http://www.brownstoner.com/forum/archives/2009/04/moving_a_refrig.php.

Fig. 2 Railings on both sides of a walkway provide flexibility in use to right- and left-handed users [b]

Principle three, Simple and Intuitive Use, is defined as "use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level." There are five guidelines to this principle including: 3a) Eliminate unnecessary complexity 3b) Be consistent with the user expectations and intuition 3c) Accommodate a wide range of literacy and language skills 3d) Arrange information consistent with its importance and 3e) Provide effective prompting and feedback during and after task completion. Powered seat controls arranged in the shape of a seat provide simple and intuitive use as shown in Fig. 3.

[b] Actionironusa.com, 2010, "Handrails," http://actionironusa.com/ornamental-iron-products.html

Fig. 3 Powered seat controls arranged in the shape of a seat provide simple and intuitive use [c]

Principle four, Perceptible Information, is defined as "the design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities." There are four guidelines to this principle including: 4a) Use different modes (pictorial, verbal, tactile) for redundant presentation of essential information 4b) Maximize "legibility" of essential information 4c) Differentiate elements in ways that can be described and 4d) Provide compatibility with a variety of techniques or devices used by people with sensory limitations. Closed captioning provides perceptible information for users with hearing disabilities as shown in Fig. 4.

[c] Gold, A., 2008, "Excellent Power Seat Controls," http://cars.about.com/od/mercedesbenz/ig/2008-Mercedes-E320-Diesel-pics/2008-Mercedes-E320-seat-ctrls.htm

Fig. 4 Closed captioning provides perceptible information for hearing impaired users [d]

Principle five, Tolerance for Error, is defined as "the design minimizes hazards and the adverse consequences of accidental or unintended actions." There are four guidelines to this principle including: 5a) Arrange elements to minimize hazards and errors: most used elements, most accessible; hazardous elements eliminated, isolated, or shielded 5b) Provide warning of hazards and errors 5c) Provide fail safe features and 5d) Discourage unconscious action in tasks that require vigilance. Hand guards on a bagel cutter provide tolerance for error as shown in Fig. 5.

Fig. 5 Hand guards on this bagel cutter provide tolerance for error [e]

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[d] Stanford University, 2009, "Why Captioning?," http://captioning.stanford.edu/
[e] Decuisine.co.uk, 2010, "Bagel Slicer," http://www.decuisine.co.uk/cookshop/kitchen_tools_gadgets/bagel-slicer.html

Principle six, Low Physical Effort, is defined as “the design can be used efficiently and comfortably and with a minimum of fatigue.” There are four guidelines to this principle including: 6a) Allow user to maintain a neutral body position 6b) Use reasonable operating forces 6c) Minimize repetitive actions and 6d) Minimize sustained physical effort. The trigger locking feature on gas pumps provide low physical effort by minimizing sustained physical effort as shown in Fig. 6.

Fig. 6 Trigger locking mechanisms on gas pumps provide low physical effort to the user [f]

Principle seven, Size and Space for Approach and Use, is defined as “appropriate size and space is provided for approach, reach, manipulation, and use regardless of user’s body size, posture, or mobility.” There are four guidelines to this principle including: 7a) Provide a clear line of sight to important elements for any seated or standing user 7b) Make reach to all components comfortable for any seated or standing user 7c) Accommodate variations in hand and grip size and 7d) Provide adequate space

[f] Allamericanpatriots.com, 2009, "Gas Pump Nozzle," http://www.allamericanpatriots.com/photos/gas-pump-nozzle

for the use of assistive devices or personal assistance. Larger restroom stalls with multiple grab bars provide size and space for approach and use to users in wheelchairs as shown in Fig. 7.

Fig. 7 Large restrooms with multiple grab bars provide size and space for approach and use to users in wheelchairs [g]

2.2 Functional Modeling with the Functional Basis

Functional modeling in systems engineering is the structured representation of functions and processes within the modeled system. These functions and processes are described using the Functional Basis, a standardized vocabulary widely used among the product design community. An introduction to the Functional Basis is first visited, followed by a background of functional modeling.

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[g] Poggio, N., 2004, "Exhibition Design Guidelines," http://users.ices.utexas.edu/~natacha/CATTt/mobility.html

2.2.1 Functional Basis

Within functional modeling, a standardized set of function related terminology is required to produce repeatable and meaningful results. Hirtz et al. [8] reconciled and integrated several research efforts to formulate a versatile and comprehensive design vocabulary known as the reconciled Functional Basis. Table 1 and Table 2 show a sample of Functional Basis flows and functions, respectively.

Table 1 This sample of the Functional Basis shows the hierarchy of flows [8]

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Material	Human		Hand, foot, head
	Gas		Homogeneous
	Liquid		Incompressible, compressible, homogeneous,
	Solid	Object	Rigid-body, elastic-body, widget
		Particulate	
		Composite	
	Plasma		
	Mixture	Gas-gas	
		Liquid-liquid	
		Solid-solid	Aggregate
		Solid-Liquid	
		Liquid-Gas	
		Solid-Gas	
		Solid-Liquid-Gas	
		Colloidal	Aerosol

Table 2 This sample of the Functional Basis shows the hierarchy of functions [8]

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack

Functional descriptions are generally expressed in a verb-object format where a function term takes the verb position and a flow term takes the object position as described in [9]. For consistency, the functional models in this research use function and flow descriptions of the Secondary hierarchy only.

2.2.2 Functional Modeling

A functional model graphically represents the sequence of functions and flows of materials, energies, and signals within a system. Before a functional model exists, a black box model is created based on the needs of the customer and represents the product's overall functionality including required flows. A black box model for a manual can opener is shown in Fig. 8 to illustrate this idea.

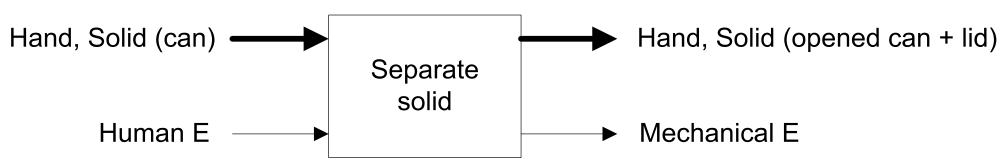


Fig. 8 The high level transformation of functions and flows is termed black box model and shown here representing the overall functionality of a manual can opener

The verb-object functional descriptions are used within a block diagram element with energy flows represented by thin, solid arrows; material flows represented by thick, solid arrows and signal flows represented by dashed arrows. These flows are decomposed into a chain of functional transformations for each flow and then aggregated to form a functional model. Fig. 9 illustrates a functional model for the manual can opener example.

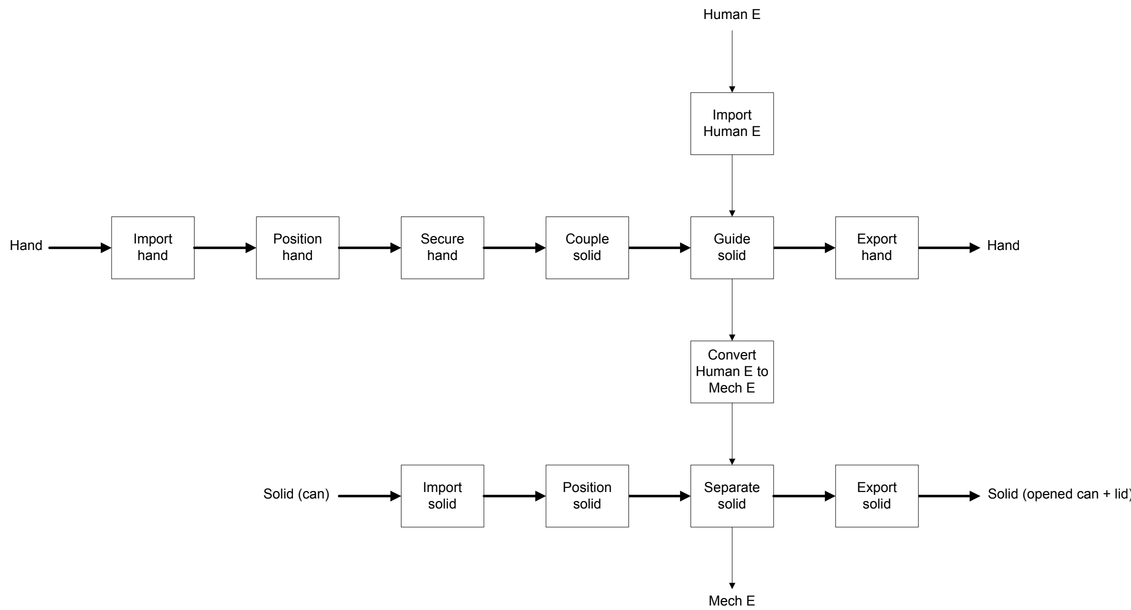


Fig. 9 A black box model is decomposed into a functional model showing the transformation of flows. This is a functional model for the manual can opener

2.3 Actionfunction Diagrams with ICF Terminology

An actionfunction diagram is created by meshing a functional model with a user activity diagram. This single graphical representation relates product function with user activity. User activities are described using ICF terminology, a classification describing health and disability. The ICF terminology is first introduced followed by the process of creating actionfunction diagrams.

2.3.1 ICF Terminology

The ICF is a classification of health and health-related domains. The World Health Organization (WHO) is the directing and coordinating authority for health within the United Nations system. The ICF is WHO's framework for measuring health and disability at both individual and population levels and acknowledges that all humans can experience some degree of disability. Moreover, the ICF considers the social facets of disability and does not distinguish disability only as medical or biological dysfunction [10].

These domains are classified into four components and include Body Structures, Body Functions, Activity and Participation, and Environmental Factors within which are nested groups of second-, third-, and sometimes fourth-level categories. These categories are the units of classification and each successive level can be used to further refine the code, or level of detail recorded; the user chooses the level appropriate to the classification [11]. Qualifiers are numeric measures coded after the relevant category code to provide the extent of the problem in relation to the impairment or limitation.

For example, the code s250.28 is recorded for a person experiencing a moderate problem with the structure of the middle ear, where s denotes the component, in this case Body Structures; the first digit (2) denotes the domain, i.e. the eye, ear and related structures; the second and third digits (50) denote the second-level category, i.e. structure of the middle ear; the first digit after the decimal point (2) denotes the generic qualifier, indicating, in this case, a moderate impairment with the middle ear; and the second digit after the decimal point (8) indicates, in this case, that the nature of the impairment is not specified [11]. In this research, we are only concerned with the body structure and functions related to a specific user activity, thus omit the use of qualifiers after the decimal point when using the ICF code.

2.3.2 Actionfunction Diagrams

Every consumer product involves a distinct sequence of activities the user must perform to use the product. In most cases a product is purchased, transported, assembled out of packaging, stored away, removed for use, initialized, used in different ways in different environments, perhaps modified by the user, periodically cleaned or maintained, and disposed [12]. The mapping of these user activities is known as an activity diagram. In this research, we are only concerned with the user activities associated with using the product as shown in Fig. 10 with the manual can opener example. The user activities are in terms of ICF Activities and Participation descriptors.

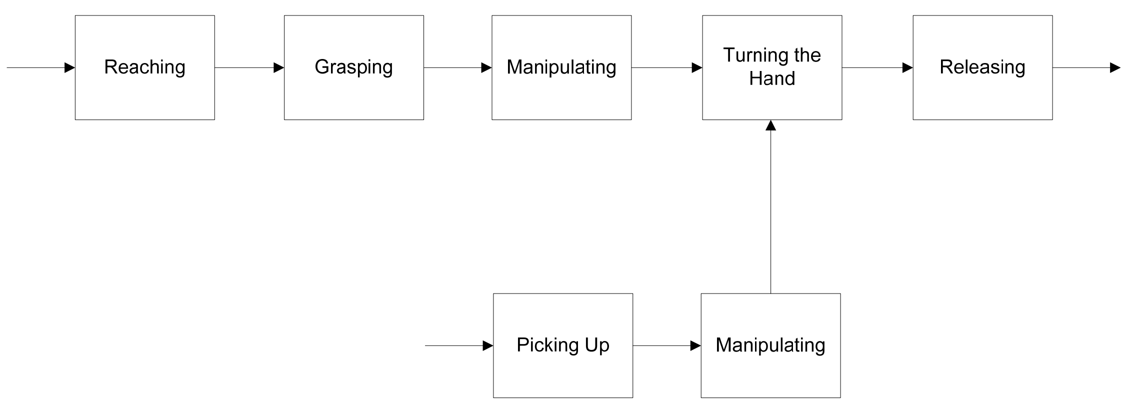


Fig. 10 User activities of the manual can opener are mapped together to form an activity diagram

With one hand, for example the right hand, the user reaches for the can opener then grasps it. With the left hand, the user picks up a can and manipulates it towards the can opener. The right hand then manipulates the can opener to the can lid before turning to operate the can opener. Finally, the user releases the right hand from the can opener and the overall function of opening a can is complete.

To illustrate the relationship between user activities and product functions, activity diagrams and functional models can be combined into a single graphical representation called an actionfunction diagram. This practice was first presented by Kostovich et al. [13] in their analysis of twenty universal and typical product pairs. The actionfunction diagram for the manual can opener is shown in Fig. 11. Actionfunction diagrams provide us with a more complete mental picture of the relation between user activities and product functions to facilitate product design improvements.

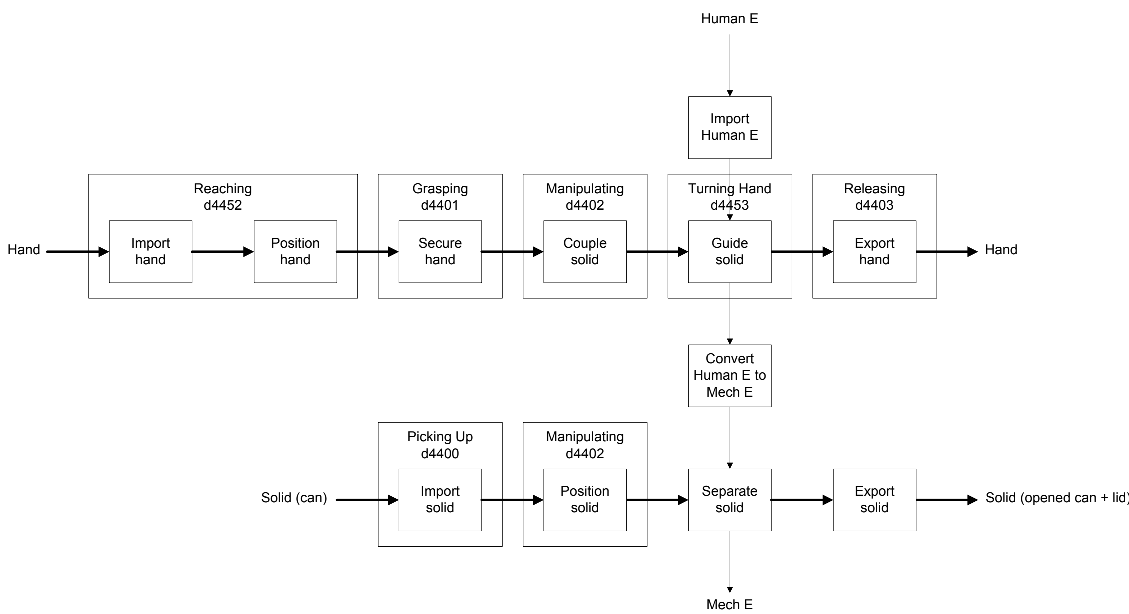


Fig. 11 The actionfunction diagram for the manual can opener shows the relation between user activities and product functions

2.4 Association Rules

In data mining, the process of extracting patterns from data, association rule-based learning is a method for discovering interesting relations between variables of a given dataset. The method of mining association rules was first introduced by Agrawal et al. [14]. Let $I = \{i_1, i_2, \ldots, i_n\}$ be a set of binary attributes, called items. Let $T = \{t_1, t_2, \ldots t_m\}$ be a set of transactions called the database. Each transaction in T is unique and contains a subset of the items in I. An association rule is defined as an implication of the form $X \rightarrow Y$ where $X, Y \subseteq I$ and $X \cap Y = \emptyset$. The itemsets X and Y are called the antecedent and consequent of the rule, respectively. Association rules provide us with information in the form of "If-Then" statements, with the antecedent item set being the "If" and the consequent item set being the "Then".

Association rules are defined to have several properties based on the incidence of the antecedent and consequent item sets in the database and describe the degree of uncertainty about the rule. The support of the rule $sup(X \rightarrow Y)$ is the proportion of transactions that include all items in the antecedent and consequent parts of the rule. The support can be viewed as the probability that a randomly selected transaction from the database will contain all items in the antecedent and consequent. The confidence $conf(X \rightarrow Y)$ of the rule, also known as strength, is the proportion of transactions that include all items in the consequent and antecedent to the transactions that include all items in the antecedent. The confidence can be viewed as the conditional probability that a randomly selected transaction will include all the items in the consequent given that the transaction includes all the items in the antecedent.

$$conf(X \rightarrow Y) = \frac{sup(X \rightarrow Y)}{sup(X)} \tag{1}$$

Finally, the lift of the rule *lift*($X \rightarrow Y$) is the proportion of the rule confidence to the transactions that include all items in the consequent. Lift can be described as the ratio of observed rule support to that expected by chance.

$$lift(X \rightarrow Y) = \frac{conf\,(X \rightarrow Y)}{sup(Y)} \tag{2}$$

The availability of detailed customer transactions from using bar code scanners has led to what is known as a market basket analysis. Stores such as supermarkets record customer transactions to know if certain groups of items are consistently purchased together. This data could be used for store layouts to place items optimally with respect to each other, they could use such information for cross-selling, for promotions, for catalog design and to identify customer segments based on buying patterns [15]. For example, suppose the itemset I = {water, peanut butter, soap, jelly, bread, cereal} and consider the rule {peanut butter, jelly} → {bread} [16]. A support value of 0.03 for this rule means that peanut butter, jelly, and bread appeared together in 3% of the market baskets. A confidence of 0.82 for this rule implies that when peanut butter and jelly were purchased, 82% of the time bread was also purchased. If bread appeared in 43% of all market baskets then the rule {peanut butter, jelly} → {bread} would have a lift of 1.907.

2.5 Apriori Algorithm

Generating association rules from a transactional database requires an algorithm to search and extract rules which exceed two user specified thresholds, a minimum support and minimum confidence level. Traditionally, algorithms for discovering frequent itemsets make multiple passes over the data. In the first pass, the support of individual items is counted to determine which ones are frequent, i.e. have minimum support. Each subsequent pass starts with a seed set of itemsets found to be frequent from the previous pass. This seed set is used to generate new potentially frequent itemsets, called candidate itemsets, and the actual support of these candidate itemsets is counted during the pass over the data. At the end of the pass, it is determined which of the candidate itemsets are actually frequent, and they become the seed for the next pass. This process continues until no new frequent itemsets are found.

The Apriori algorithm proposed by Agrawal and Srikant [17] is the most typical among association rule discovery algorithms and operates differently from traditional algorithms in terms of which candidate itemsets are counted during a data pass and in the way those candidate itemsets are generated. The Apriori algorithm generates the candidate itemsets to be counted in a pass by using only the itemsets found frequent in the previous pass without considering the transactions in the database. This algorithm operates on the intuition that any subset of a frequent itemset must be frequent making it more efficient since it generates a much smaller number of candidate itemsets. The Apriori algorithm is also capable of generating rules with more than one item in the consequent unlike traditional algorithms.

3. PREVIOUS WORK

Reviewing product design literature reveals that association rule-based learning has yet to be used to improve universal design. There has been however, research to improve universal design [3-7, 13] as well as applying association rule-based learning to product design attributes and manufacturing [18, 19].

Beecher and Paquet [4] developed a usability testing survey instrument to analyze how well consumer products complied with established universal design principles. Thirty-six adult users performed standardized tasks with pens, food storage containers, pliers, and calculators, and for each task responded to a preliminary set of survey items and rated task difficulty. Analysis of the survey responses resulted in eleven factors which correspond well with the seven principles of universal design. The development and testing of this survey is one of the first attempts to formally apply principles of universal design to the consumer product design process.

Kostovich et al. [13] present a product analysis framework to improve universal design research and practice. The authors explored the relationship between user activity, product function, and product form as it pertains to differences in typical and universal product pairs. Activity diagrams and functional models were combined into a single graphical representation called an actionfunction diagram to illustrate parametric, morphological, and functional differences between the typical and universal products that satisfy the same overall need. It was found that within the products studied, the majority of differences between universal and typical products are related to user hand manipulation of the product. Functions not related to human flows and those which are internal to the product generally remained unchanged.

Li et al. [18] applied association rule-based learning to product design in attempt to acquire knowledge among design attributes based on discrete domain knowledge. Their work was applied in a case application involving the form selection of gate valves. Several product design parameters with strong constraint relations including working medium, nominal pressure, working temperature, and nominal diameter were tabulated for a set of different model gate valves. Using an unspecified algorithm, association rules were produced for the data set. For example, (nominal pressure of 10-80, working medium of water and steam) → (wedge disc design is wedge and single) with 8.3% support and 65.2% confidence showing wedge and single gate valves fit situations of high pressure and low viscidity medium.

Shahbaz et al. [19] applied association rule methods to product manufacture and operational data from manufacturing industries. The dimensions of a finished product are a good measure of production cycle quality and help in recommending design alterations and identifying relations between different dimensions resulting from manufacturing. A case study was performed using dimensional data obtained during a fan blade manufacture. In this study, the data is the result of a highly controlled manufacturing process. Thus the authors were interested in unusual combinations of results representing problem situations. For example, some rules indicated that a certain nominal dimension corresponded to another dimension being non-nominal. This type of result provided valuable feedback for the design process and could help in redefining design constraints.

Previous work in universal design and association rule-based learning is too broad for specific product design implementation. The product pair study is the first attempt at identifying design changes between typical and more universal products. Still, product designers need guidelines to follow when pursuing universal design at the conceptual level.

4. RESEARCH APPROACH

The research in this study is mapped as shown in Fig. 12. Background on functional modeling, activity diagrams, actionfunction diagrams, and association rule-based learning has been covered in section 2. The product pair studies, design changes, and association rule generation and selection are covered in this Section.

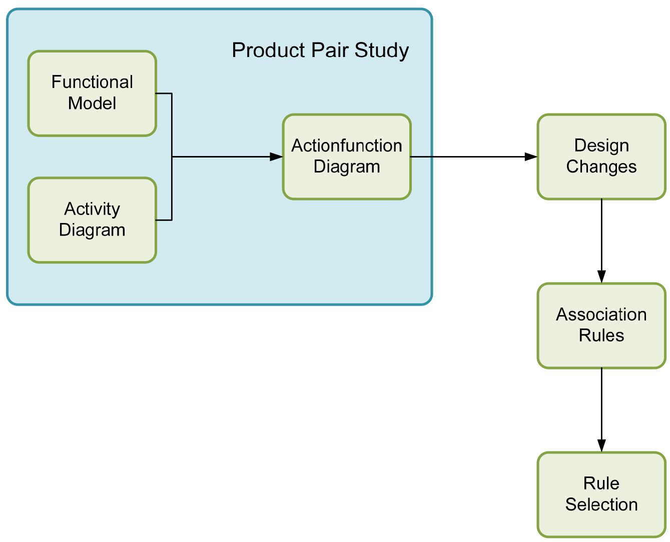


Fig. 12 The research methodology begins with a product pair study and concludes with the generation and selection of universal design rules

4.1 Product Pair Study

The fourteen typical and universal product pairs studied in this research were taken from Kostovich et al. [13] to further investigate the relation between product function and user activity and the application of association rule-based learning. Product pairs are defined to be two products with similar functionality that satisfy the same high level need but are different by design, as shown with the can opener product pair in Fig. 13.

Fig. 13 The can opener product pair consists of a manual can opener being the typical product and the electric can opener being the more universal design [h] [i]

The typical product is basic in design, such as the manual can opener, and the universal product of this product pair would be an electric can opener. The overall functionality of the fourteen product pairs are diverse in application and include arm chairs, box cutters, can openers, car ingress systems, pruners, phones, car drive controls, recliners, scissors, signage, toilets, remotes, sinks, and food storage containers. We will continue to use the can opener product pair as an example in presenting the remainder of this section.

First, functional models and activity diagrams were constructed for both the typical and universal can opener designs. These were then combined to form an actionfunction diagram for both products of the pair. The actionfunction diagram for the typical and universal can opener designs is shown in Fig. 14 and Fig. 15, respectively.

[h] Bishop, K., 2009, "Items to Hoard," http://preparednesspro.wordpress.com/2009/02/

[i] Amazon.com, 2009, "Black & Decker Gizmo Electric Can Opener," http://www.amazon.com/Black-Decker-GC200-Gizmo-Opener/dp/B00005MF94

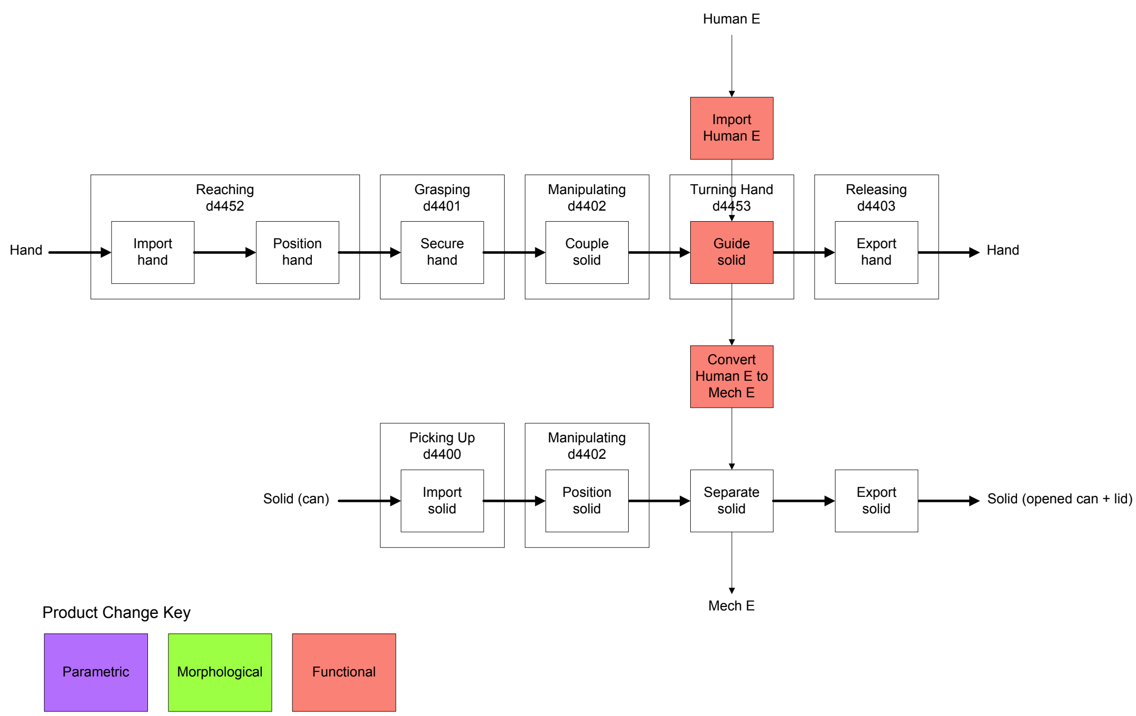


Fig. 14 The actionfunction diagram for the typical manual can opener design

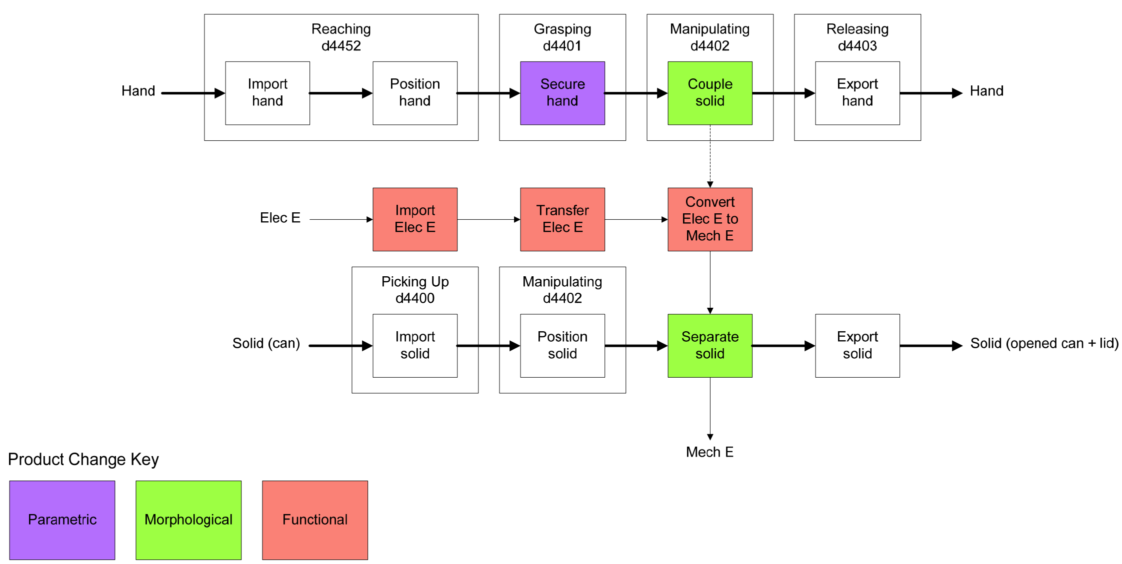


Fig. 15 The actionfunction diagram for the more universal electrical can opener design

To reflect product changes between the typical and universal products, we must consider the three categories of design changes introduced in [13] termed as parametric, morphological, and functional changes. A parametric change is a scalable difference for the same solution of the same function. For example, if the product function was secure hand and the solution was a handle, a wider or more ergonomically designed handle would be a parametric change from a thin and cumbersome handle. A morphological change involves a different solution for the same function. If the product function was convert human energy to mechanical energy, a four-bar linkage system is morphologically different than a spring since they are different solutions to the same function. A functional change involves adding or subtracting functionality between the product pair. Automating a product to make it more universal involves several functional changes considering electrical energy must be imported, stored, and transferred [20]. The color scheme used to represent the three design changes is shown in the product change key of Fig. 14 and Fig. 15.

The can opener product pair will be revisited to show how design changes between the two designs were analyzed. The universal can opener design contains one parametric change due to the different contour of the can opener which fits the user's palm when grasping the product to satisfy the function secure hand. The first morphological change is the user must manipulate the universal can opener differently than a typical can opener to satisfy the same function of couple solid when coupling the can opener to the can. The second morphological change involves the function separate solid; the typical can opener design uses two serrated wheels whereas the universal design uses one serrated wheel and one sharp blade to open the can, or separate the solid. Since the universal can opener is automated, there are several functionality additions and subtractions when moving from the typical to universal design. As shown in Fig. 14 and Fig. 15, the functions import human energy, guide solid as done via turning the hand, and convert human energy to mechanical energy are eliminated in the universal design since the functions import electrical energy, transfer electrical energy, and convert electrical energy to mechanical energy are added to automate the can opener and eliminate the need for the user to turn a handle and exert human energy.

Actionfunction diagrams were created and product changes were identified for all typical and universal products in this study. The product changes were recorded in a spreadsheet as in Table 3 showing the can opener example.

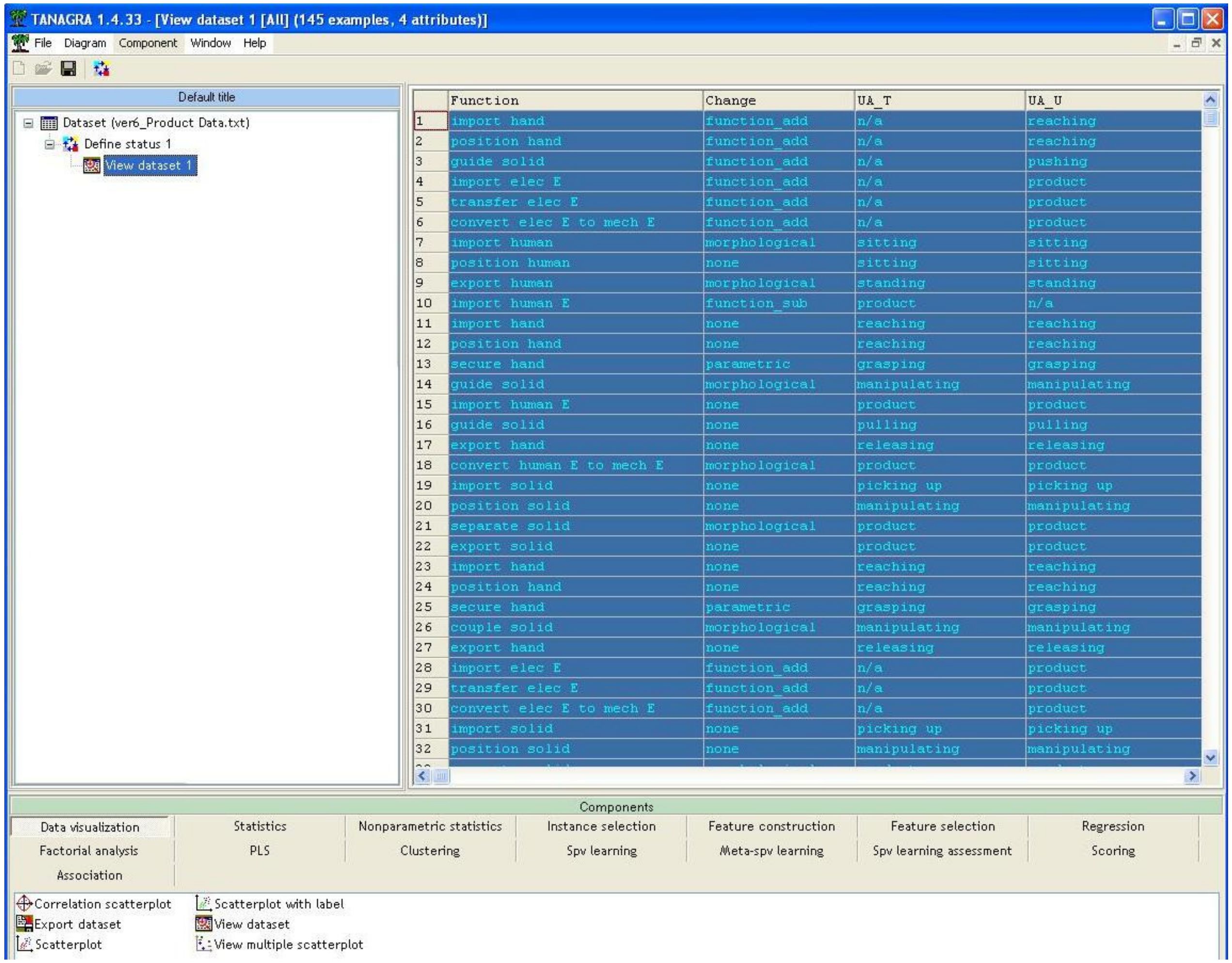
Table 3 Product changes when moving from a typical to universal design were recorded with the corresponding product function as well as the typical (UA_T) and universal user activity (UA_U)

Product	Function	Change	UA_T	UA_U
can opener	import hand	none	reaching	reaching
	position hand	none	reaching	reaching
	secure hand	parametric	grasping	grasping
	couple solid	morphological	manipulating	manipulating
	export hand	none	releasing	releasing
	import elec E	function_add	n/a	product
	transfer elec E	function_add	n/a	product
	convert elec E to mech E	function_add	n/a	product
	import solid	none	picking up	picking up
	position solid	none	manipulating	manipulating
	separate solid	morphological	product	product
	export solid	none	product	product
	import human E	function_sub	product	n/a
	guide solid	function_sub	turning the hand	n/a
	convert human E to mech E	function_sub	product	n/a

Since we are concerned with the relation between user activity and product function when making typical products more universal, the product changes when moving from the typical to universal product design were recorded. The corresponding product function was recorded as well as the typical and universal user activities. This was done to track whether the user activity remained the same, changed, or shifted to the product for a given design change. Each row of the spreadsheet constitutes an itemset to be used in generating association rules. Each itemset is of size four containing product function (Function), product change (Change), user activity of the typical product (UA_T), and user activity of the universal product (UA_U).

4.2 Association Rule Generation and Selection

As mentioned in Section 2.4, the Apriori algorithm is the well studied and very efficient at extracting rules from transaction databases. Tanagra, data mining software designed primarily for research use [21], was used in this research to run the Apriori algorithm. The Tanagra software was chosen among other available data mining software packages due to its graphical interface and free cost.



	Function	Change	UA_T	UA_U
1	import hand	function_add	n/a	reaching
2	position hand	function_add	n/a	reaching
3	guide solid	function_add	n/a	pushing
4	import elec E	function_add	n/a	product
5	transfer elec E	function_add	n/a	product
6	convert elec E to mech E	function_add	n/a	product
7	import human	morphological	sitting	sitting
8	position human	none	sitting	sitting
9	export human	morphological	standing	standing
10	import human E	function_sub	product	n/a
11	import hand	none	reaching	reaching
12	position hand	none	reaching	reaching
13	secure hand	parametric	grasping	grasping
14	guide solid	morphological	manipulating	manipulating
15	import human E	none	product	product
16	guide solid	none	pulling	pulling
17	export hand	none	releasing	releasing
18	convert human E to mech E	morphological	product	product
19	import solid	none	picking up	picking up
20	position solid	none	manipulating	manipulating
21	separate solid	morphological	product	product
22	export solid	none	product	product
23	import hand	none	reaching	reaching
24	position hand	none	reaching	reaching
25	secure hand	parametric	grasping	grasping
26	couple solid	morphological	manipulating	manipulating
27	export hand	none	releasing	releasing
28	import elec E	function_add	n/a	product
29	transfer elec E	function_add	n/a	product
30	convert elec E to mech E	function_add	n/a	product
31	import solid	none	picking up	picking up
32	position solid	none	manipulating	manipulating

Fig. 16 **This screenshot shows the imported product pair itemset data in the Tanagra software [21]**

First, the spreadsheet containing the product pair itemset data was imported into Tanagra as a dataset. This is done when creating a new project and the user is prompted to specify the data source file to be used as a dataset. Fig. 16 shows a screenshot of Tanagra with the imported data and the four items of interest including product function (Function), product change (Change), user activity of the typical product (UA_T), and user activity of the universal product (UA_U).

Next, the Apriori component is added to the data operation tree in the left pane of Tanagra under the dataset component. The Apriori parameters were set to run based on a minimum confidence level of 0.70, or 70%, and minimum support level of 0.005, or 0.5%. It is preferred to have rules whose confidence (strength) level approaches 100%; however, the minimum confidence level was set at 70% to extract more rules to be manually reviewed in case some interesting rules had a lower confidence level. The minimum support level was set at a very low 0.5% based on the notion that support is a value that implies statistical significance [22]. Rarely occurring data in the database may be significant enough to use despite its low support level due. After the minimum confidence and support parameters are set, the Apriori algorithm is run on the data to produce association rules. Fig. 17 is a screenshot showing a fraction of the association rules mined with Tanagra.

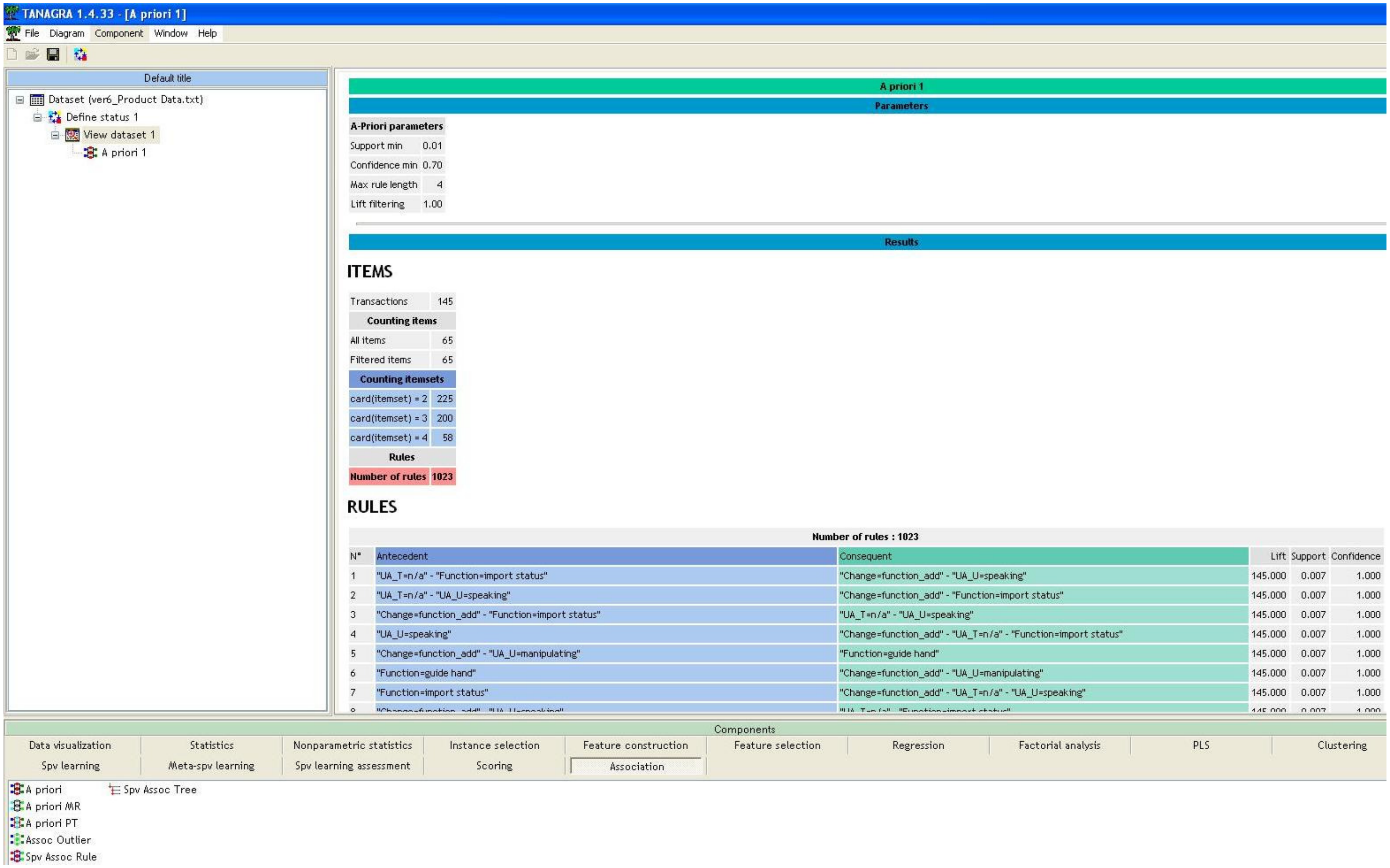


Fig. 17 A fraction of the association rules mined with Tanagra are shown in this screenshot [21]

Mined association rules will contain at least one item in the antecedent and consequent parts of the rule since all configurations of the itemset will be considered in the Apriori algorithm. This requires a manual rule selection process. As stated earlier, our research objective is to apply association rule-based learning to product pairs and develop universal design rules to be used during the conceptual design phase. In the conceptual design phase, designers are working with functional models and more importantly, actionfunction diagrams illustrating the relation between product function and user activity. Therefore, it is important for designers to know what design changes should be implemented given user activity and product function to make a product more universal. As a result of design changes, designers also want to know if user activity corresponds with product function as before or differently. This implies that we are searching for association rules mined with product function (Function) and user activity of the typical product (UA_T) in the rule antecedent, and product change (Change) and user activity of the universal product (UA_U) in the rule consequent. For clarification, rules will have the following form:

(Function, Typical User Activity) → (Change, Universal User Activity).

5. RESULTS

The Apriori algorithm within Tanagra mined 1,023 association rules which contained at least one item of the product function (Function), product change (Change), user activity of the typical product (UA_T), and user activity of the universal product (UA_U) itemset in both the antecedent and consequent. Rules were down-selected based on the prescribed rule form. The remaining 29 rules are shown in Table 4 sorted by increasing complexity of design change. Each rule is explained in the following sub-sections.

5.1 Rules

5.1.1 (Import Solid, Picking Up) → (None, Picking Up)

Table 4 shows that no design change is needed for the import solid function done by the user activity of picking up as specified in this rule. A product requiring the user to pick up and import a solid into its system cannot be made more universal with a design change to the import solid function. For example, in order for the user to cut the solid cardboard in Fig. 18, the user must pick up and import the solid into the product system of the scissors regardless the design of the scissors. This rule stems from the box cutter, can opener, pruner, scissor, and food container product pair studies. This rule could be applied to any product which requires a solid to be imported into the product system. Often, these products perform work on the solid such as separating or changing the shape of the solid. In the food container product pair study, the imported solid is stored instead.

Table 4 Only 29 association rules remain after the 1,023 mined association rules were down selected based on the rule selection process and are organized by degree of product change

Antecedent		**Consequent**		**Measures**		
User Activity - Typical	**Function**	**Change**	**User Activity - Universal**	**Sup. (%)**	**Conf. (%)**	**Lift**
pulling	guide solid	none	pulling	2.1	100	48.3
picking up	import solid	none	picking up	3.4	100	29.0
manipulating	position solid	none	manipulating	3.4	100	20.7
releasing	export hand	none	releasing	5.5	80	12.9
product	import liquid	none	product	0.7	100	8.5
product	export solid	none	product	2.8	100	8.5
product	export control signal	none	product	1.4	100	8.5
product	transfer liquid	none	product	0.7	100	8.5
product	export liquid	none	product	0.7	100	8.5
reaching	position hand	none	reaching	6.2	90	7.3
reaching	import hand	none	reaching	6.2	90	7.3
manipulating	separate solid	parametric	pulling	0.7	100	145.0
comm with written msgs	indicate status	morphological	comm with written msgs	0.7	100	145.0
pushing with lower extremity	convert human E to mech E	morphological	pushing	0.7	100	145.0
standing	export human	morphological	standing	2.1	100	48.3
product	actuate hydraulic E	morphological	product	0.7	100	18.1
product	actuate liquid	morphological	product	0.7	100	18.1
turning the hand	guide solid	function_sub	n/a	1.4	100	9.7
n/a	import status	function_add	speaking	0.7	100	145.0
n/a	guide hand	function_add	manipulating	0.7	100	145.0
n/a	export hand	function_add	pulling	0.7	100	145.0
n/a	guide solid	function_add	pushing	2.1	75	36.3
n/a	position hand	function_add	reaching	2.8	100	18.1
n/a	import hand	function_add	reaching	2.8	100	18.1
n/a	sense status	function_add	product	0.7	100	8.1
n/a	transfer elec E	function_add	product	3.4	100	8.1
n/a	sense hand	function_add	product	0.7	100	8.1
n/a	convert elec E to mech E	function_add	product	3.4	100	8.1
n/a	import elec E	function_add	product	3.4	100	8.1

Fig. 18 A design change cannot make importing a solid via picking up, positioning a solid via manipulating, or exporting a solid more universal. These functions are required for products such as scissors to be functional whether the typical (top right) or universal design (bottom right) is used [j k l]

5.1.2 (Position Solid, Manipulating) → (None, Manipulating)

Table 4 shows that no design change is needed for the position solid function done by the user activity of manipulating as specified in this rule. A product requiring the user to manipulate and position a solid to its system cannot be made more universal with a design change to the position solid function. For example, in order for the user to cut the solid cardboard in Fig. 18, the user must position the solid before cutting regardless the design of the scissors. This rule stems from the box cutter, can opener, pruner, scissor, and food container product pair studies. In the product pair studies, the function position solid always followed the function import solid. This rule could be applied to any product which requires a solid to be positioned to the product system. Often, these products perform work on the solid such as separating or changing the

[j] Countryliving.com, 2009, "Letter-Perfect Craft Ideas," http://www.countryliving.com/crafts/letter-perfect-craft-0908
[k] Lymeeregis.com, 2009, "Paul's Men's Hairdressers," http://www.lymeregis.com/shops-and-hairdressers/index.htm
[l] Amazon.com, 2009, "Fiskars Softouch Multi-Purpose Scissors," http://www.amazon.co.uk/Fiskars-9911-7097-Softouch-Multi-Purpose/dp/B00006IFNC

shape of the solid. In the food container product pair study, the positioned solid is stored instead.

5.1.3 (Export Solid, Product) → (None, Product)

Table 4 shows that no design change is needed for the export solid function as specified in this rule. This function typically does not involve user activity since the product exports the solid from its system. A product requiring a solid to be exported from its system cannot be made more universal with a design change to the export solid function. For example, after the user cuts the solid cardboard in Fig. 18, the solid is exported from the product system in the same manner regardless the design of the scissors. This rule stems from the box cutter, can opener, pruner, and scissor product pair studies. This rule could be applied to any product which requires a solid to be exported from the product system. Often, these products perform work on the solid such as separating or changing the shape of the solid.

5.1.4 (Guide Solid, Pulling) → (None, Pulling)

Table 4 shows that no design change is needed for the guide solid function done by the user activity of pulling as specified in this rule. A product requiring the user to pull and guide a solid within its system cannot be made more universal with a design change to the guide solid function. For example, to cut the paper as shown in Fig. 19, both the typical and universal box cutter designs require the same pulling user activity to guide the solid (box cutter). Guiding a solid may seem more universal in some products but the design change occurs with other functions; for example, the more universal box cutter design contains a parametric design change for the secure hand function with its handle and a morphological design change for the separate solid function with the rotary blade. This rule stems from the box cutter, car ingress, and car operation product pair studies. The car ingress and car operation product pair studies employ the guide solid function when opening a car door. This rule could be applied to any product which requires a solid to be guided within a product system.

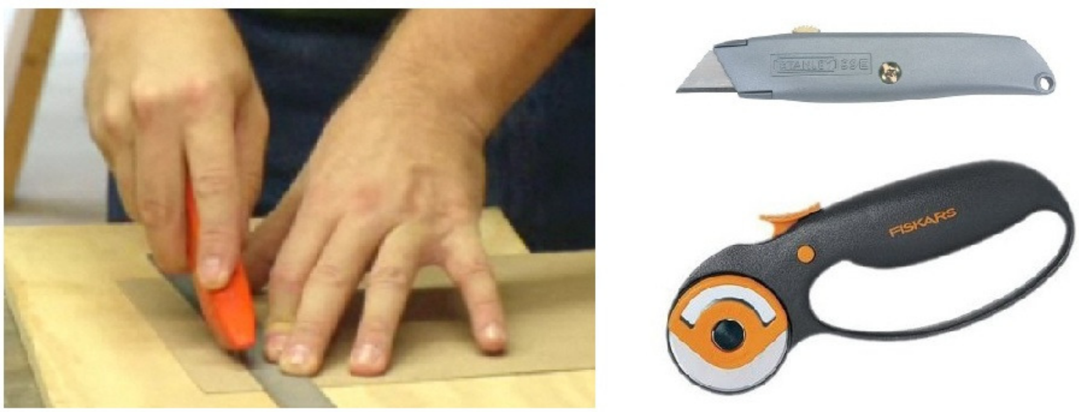


Fig. 19 A design change cannot make the user activity of pulling to guide a solid more universal. The typical (top right) and universal (bottom right) box cutter designs both require a pulling motion to cut solids [m] [n] [o]

5.1.5 (Import Liquid, Product) → (None, Product)

Table 4 shows that no design change is needed for the import liquid function as specified in this rule. This function typically does not involve user activity since the product imports the liquid to its system. A product requiring a liquid to be imported to its

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[m] Ehow.com, 2009, "How to Use a Box Cutter Safely," http://www.ehow.com/video_5538450_use-box-cutter-safely.html
[n] Constructionandmasonrysupply.com, 2009, "Utility Knife," http://constructionandmasonrysupply.com/index.php?main_page=product_info&cPath=12&products_id=34
[o] Amazon.com, 2009, "Fiskars 45mm Rotary Cutter," http://www.amazon.com/Fiskars-95217097-45-Rotary-Cutter/dp/B000B7M8WU

system cannot be made more universal with a design change to the import liquid function. For example, water is imported to the sink faucets in Fig. 20 from a supply header in the same manner regardless the design of the sink faucet. This rule solely comes from the sink faucet product pair study. This rule could be applied to any product which requires a liquid to be imported to the product system such as any type of household dispenser.

Fig. 20 The typical (left) and universal (right) sink faucet designs both require import liquid, transfer liquid, and export liquid functions to be functional. No product changes can make these product functions more accessible [p] [q]

5.1.6 (Transfer Liquid, Product) → (None, Product)

Table 4 shows that no design change is needed for the transfer liquid function as specified in this rule. This function typically does not involve user activity since the product transfers the liquid within its system. A product requiring a liquid to be transferred within its system cannot be made more universal with a design change to the

[p] Deltafaucet.com, 2009, "Classic Two Handle Centerset Lavatory Faucet," http://www.deltafaucet.com/bath/details/2520LF-MPU.html
[q] Sloanvalve.com, 2009, "Optima On-Q Faucets," http://www.sloanvalve.com/Our_Products/Optima_On-Q_Faucets.aspx

transfer liquid function. For example, water is transferred through the sink faucets in Fig. 20 in the same manner regardless the design of the sink faucet. This rule solely comes from the sink faucet product pair study. In the product pair study, the function transfer liquid always followed the function import liquid. This rule could be applied to any product which requires a liquid to be transferred within the product system such as any type of household dispenser.

5.1.7 (Export Liquid, Product) → (None, Product)

Table 4 shows that no design change is needed for the export liquid function as specified in this rule. This function typically does not involve user activity since the product exports the liquid from its system. A product requiring a liquid to be exported from its system cannot be made more universal with a design change to the export liquid function. For example, water exits the sink faucets in Fig. 20 in the same manner regardless the design of the sink faucet. This rule solely comes from the sink faucet product pair study. In the product pair study, the function export liquid always followed the function transfer liquid. This rule could be applied to any product which requires a liquid to be exported from the product system such as any liquid dispenser.

5.1.8 (Export Control Signal, Product) → (None, Product)

Table 4 shows that no design change is needed for the export control signal function as specified in this rule. A product requiring a control signal to be exported from its system cannot be made more universal with a design change to the export control signal function. For example, to control a television as shown in Fig. 21, both the typical and universal remote designs require the same function of export control signal. This function may seem more universal in some products but the design change occurs with other functions; for example, the more universal remote design contains parametric design changes for the secure hand function with its shape and guide solid function with the large buttons and large text. This rule stems from the remote and phone product pair studies. The phone product pair study employs the export control signal function when placing a call. This rule could be applied to any product which requires a control signal to be exported from its product system.

Fig. 21 The typical (left) and universal (right) television remote designs are both required to export a control signal to be functional. No design change can make this product more universal when concerned with the export control signal function [r] [s]

5.1.9 (Import Hand, Reaching) → (None, Reaching)

Table 4 shows that no design change is needed for the import hand function done by the user activity of reaching as specified in this rule. A product requiring the user to

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[r] Bbc.co.uk, 2009, "How to Re-tune Your Digital TV," http://news.bbc.co.uk/local/manchester/hi/tv_and_radio/newsid_8281000/8281469.stm

[s] Goldviolin.com, 2009, "Big Button Universal Remote Control," http://www.goldviolin.com/Big_Button_Universal_Remote_Control_p/90375.htm

reach and import a hand into its system cannot be made more universal with a design change to the import hand function. For example, to reach for a pruner as shown in Fig. 22, both the typical and universal pruner designs require the same import hand function. This rule stems from the box cutter, can opener, car ingress, car operation, pruner, remote, scissor, sink faucet, and food container product pair studies. These products require a hand to be imported into the product system for both typical and universal designs. This rule could be applied to any product which requires a hand to be imported to a product system.

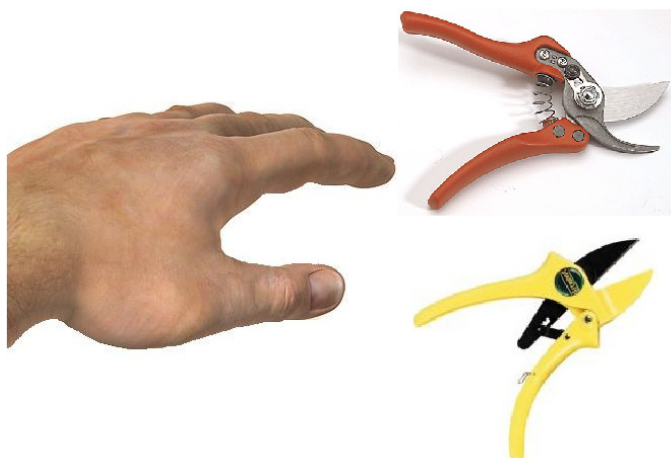

Fig. 22 The user must reach as well as release the hand from the typical (top right) and universal (bottom right) pruners in the same manner. No design changes can make the functions of import hand via reaching, position hand via reaching, or export hand via releasing more universal [t] [u] [v]

5.1.10 (Position Hand, Reaching) → (None, Reaching)

Table 4 shows that no design change is needed for the position hand function done by the user activity of reaching as specified in this rule. A product requiring the

[t] Turbosquid.com, 2009, "Human Hand," http://www.turbosquid.com/3d-models/3dsmax-photorealistic-human-hand/346035
[u] Benmeadows.com, 2009, "Hand Pruners," http://www.benmeadows.com/search/Bahco/9912
[v] Floriantools.com, 2008, "Florian 601 Ratchet Pruner," http://www.floriantools.com/RP-601R.html

user to reach and position a hand to its system cannot be made more universal with a design change to the position hand function. For example, while reaching for a pruner as shown in Fig. 22, both the typical and universal pruner designs require the same position hand function before the user secures the product. This rule stems from the box cutter, can opener, car ingress, car operation, pruner, remote, scissor, sink faucet, and food container product pair studies. These products require a hand to be positioned to the product system for both typical and universal designs. In the product pair studies, the function position hand always followed the function import hand. This rule could be applied to any product which requires a hand to be positioned to a product system.

5.1.11 (Export Hand, Releasing) → (None, Releasing)

Table 4 shows that no design change is needed for the export hand function done by the user activity of releasing as specified in this rule. A product requiring the user to release and export a hand from its system cannot be made more universal with a design change to the export hand function. For example, to release a pruner as shown in Fig. 22, both the typical and universal pruner designs require the same export hand function. This rule stems from the box cutter, can opener, car ingress, car operation, pruner, remote, scissor, sink faucet, and food container product pair studies. These products require a hand to be exported from the product system for both typical and universal designs. This rule could be applied to any product which requires a hand to be exported from a product system after use.

5.1.12 (Separate Solid, Manipulating) → (Parametric, Pulling)

Table 4 shows that a parametric design change is needed for the separate solid function done by the user activity of manipulating as specified in this rule. A product requiring the user to manipulate and separate a solid within its system can be made more universal with a parametric design change to the separate solid function. As shown in Fig. 23, the more universal food container has a larger pull tab and wider lip seal. These parametric changes transform the user activity from manipulating, requiring fine hand use, to pulling, a lower effort activity, making the product more universal. This rule solely comes from the food container product pair study. This rule could be applied to any product which requires a solid to be separated when the solid is part of the product, such as a lid or other component. The can opener, box cutter, pruner, and scissor product pairs contain the function separate solid; however, in these cases the solid referred to is the solid imported into the product system and subjected to mechanical energy to separate the solid.

Fig. 23 The user activity of manipulating and separate solid functionality together suggest a parametric design change. The need for fine hand use is eliminated and the user activity is transformed to pulling as shown here with a typical food container (left) compared to Tupperware's more universal product (right) [w] [x]

5.1.13 (Indicate Status, Communicate with Written Messages)

→ (Morphological, Communicate with Written Messages)

Table 4 shows that a morphological design change is needed for the indicate status function done by the user activity of communicating with written messages as specified in this rule. A product requiring the user to communicate with a written message and indicate some status can be made more universal with a morphological design change to the indicate status function. As shown in Fig. 24, the more universal restroom sign contains Braille in addition to the visual text and picture. The user activity remains unchanged since the user is only communicating with the product in a different way. This morphological change allows the visually impaired to still communicate with the sign, making the product more universal. This rule solely comes from the signage

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[w] Rubbermaid.com, 2009, "Easy Find Lids,"http://www.rubbermaid.com/Category/Pages/Category.aspx
[x] Qvc.com, 2009, "Tupperware Wonderlier 3-piece Bowl Set," http://www.qvc.com/qic/qvcapp.aspx/view.2/app.detail/params.item.K23607.stream.d.CM_SCID.VSTR?URL=http%3A%2F%2Fwww.qvc.com%2Fqic%2Fqvcapp.aspx%2Fview.2%2Fapp.detail%2Fparams.item.K23607.stream.d.CM_SCID.VSTR&cm_ite=10285745&cm_pla=1992680&cm_ven=CJ

product pair study. This rule could be applied to any product which requires a status indication for a written message. The ICF terminology limits this rule from being applied to products which indicate status not using written messages. For example, a fire alarm indicates status visually with flashing lights as well as auditory with loud alarms.

Fig. 24 A morphological design change is suggested for the user activity of communicate with written messages when paired with the indicate status function to make products more universal [y] [z]

5.1.14 (Convert Human Energy to Mechanical Energy, Pushing with Lower Extremity) → (Morphological, Pushing)

Table 4 shows that a morphological design change is needed for the convert human energy to mechanical energy function done by the user activity of pushing with lower extremity as specified in this rule. A product requiring the user to push with their lower extremity to convert human energy to mechanical energy can be made more universal with a morphological design change to the convert human energy to

[y] Advanceusa.com, 2007, "University of Vermont Adds Gender-Neutral Bathrooms," http://www.advanceusa.org/blog/PermaLink,guid,300ec130-185b-4453-9ece-c289f9f5f818.aspx
[z] Infolink.com, 2008, "Braille and Tactile Signs from Wood & Wood Sign Systems," http://www.infolink.com.au/c/Wood-Wood-Sign-Systems/Braille-and-tactile-signs-from-Wood-Wood-Sign-Systems-n817648

mechanical energy function. As shown in Fig. 25, the more universal car provides hand controls in addition to traditional foot pedals. The user activity is transformed from pushing with lower extremity to pushing, as in pushing with the arm and hand as defined in the ICF terminology. This morphological change allows users with lower extremity disabilities to still operate the car, making the product more universal. This rule solely comes from the car operation product pair study. This rule could be applied to any product which requires the conversion of human energy to mechanical energy done by pushing with the lower extremity such as sewing machines, scooters, and other products traditionally operated via foot pedals.

Fig. 25 The user activity of pushing with lower extremity to convert human energy to mechanical energy suggests a morphological design change to make the product more universal. The user activity is transformed to pushing (using the fingers, hands, and arms) as shown here with the car operation example [aa] [bb]

[aa] About.com, 2008, "Alternative Fuels," http://z.about.com/d/alternativefuels/1/0/O/D/-/-/08_RamCummins_driver.jpg
[bb] Accessandmobility.com, 2009, "Driving Controls 3700," http://www.accessandmobility.com/drivingcontrols.html

5.1.15 (Export Human, Standing) → (Morphological, Standing)

Table 4 shows that a morphological design change is needed for the export human function done by the user activity of standing as specified in this rule. A product requiring the user to stand and export their body from its system can be made more universal with a morphological design change to the export human function. As shown in Fig. 26, the more universal chair includes a seat lift to assist the user in standing. The user activity remains unchanged since the user is only standing in a different way. This morphological change allows users with reduced functioning of their core and lower extremity to still have the freedom to stand from sitting without assistance, making the product more universal. This rule stems from the arm chair, recliner, and toilet product pair studies. This rule could be applied to any product which requires the human body to be exported from a product system done by standing.

Fig. 26 A morphological design change is suggested for the user activity of standing and export human product function as shown here in the arm chair example [cc] [dd]

[cc] Ecodesignz.com, 2009, "Anhui Side Chair," http://www.ecodesignz.com/page/ED/PROD/Chairs/ED-02
[dd] Vitalityweb.com, 2009, "Lift Up Seat Assist Cushion," http://vitalityweb.com/backstore/Seat-assist.htm

5.1.16 (Actuate Liquid, Product) → (Morphological, Product)

Table 4 shows that a morphological design change is needed for the actuate liquid function as specified in this rule. This function typically does not involve user activity since the product actuates the liquid within its system. A product requiring a liquid to be actuated within its system can be made more universal with a morphological design change to the actuate liquid function. As shown in Fig. 20 on page 39, the more universal sink faucet actuates water flow after motion is sensed instead of requiring the user to turn the faucet knobs. This morphological change allows users with reduced functioning of their hand or arm to still actuate water flow from the sink faucet, making the product more universal. This rule solely comes from the sink faucet product pair study. This rule could be applied to any product which requires a liquid to be actuated within a product system such as any liquid dispenser.

5.1.17 (Actuate Hydraulic Energy, Product) → (Morphological, Product)

Table 4 shows that a morphological design change is needed for the actuate hydraulic energy function as specified in this rule. This function typically does not involve user activity since the product actuates the hydraulic energy within its system. A product requiring an actuation of hydraulic energy within its system can be made more universal with a morphological design change to the actuate hydraulic energy function. This rule is analogous to rule 5.1.16 but concerns the flow of energy. An actuated liquid involves motion and thus hydraulic energy. This rule solely comes from the sink faucet product pair study.

5.1.18 (Guide Solid, Turning the Hand) → (Function_sub, n/a)

Table 4 shows that a functional design change is needed for the guide solid function done by the user activity of turning the hand as specified in this rule. A product requiring the user to turn a hand and guide a solid within its system can be made more universal with a functional design change by eliminating the guide solid function. As shown in Fig. 27, the more universal can opener eliminates the need for the user to repeatedly turn their hand to guide the crank by adding electric functionality. The user activity is eliminated with the function as shown in the rule. This rule stems from the can opener and sink faucet product pair studies. The more universal sink faucet also eliminates the need for the user to turn a hand to guide a solid by adding electric functionality to sense motion from the user. This rule could be applied to any product which requires a solid to be guided by turning of the hand such as a wheel, knob, or crank.

Fig. 27 The typical can opener (left) requires the user to repeatedly turn the handle to operate. The more universal electric can opener (right) eliminates the user activity turning the hand to guide a solid

5.1.19 (Import Status, n/a) → (Function_add, Speaking)

Table 4 shows that a functional design change is needed for the import status function done by the user activity of speaking as specified in this rule. This functional design change is one where functionality is added to the product, thus the function and user activity does not occur until they are added to the product. A product can be made more universal with a functional design change by adding the import status function. As shown in Fig. 28, the more universal phone adds import status functionality to import an auditory status. This functionality addition allows the user to operate the phone without hand use, making the product more universal. The user activity of speaking is added with the function as shown in the rule. This rule solely comes from the phone product pair study. This rule could be applied to any product where voice activation functionality can be added.

Fig. 28 The more universal phone (right) shows a functional design change by adding the import status function and speaking user activity [ee] [ff]

[ee] Cisco.com, 2009, "Cisco Unified IP Phone," http://www.cisco.com/en/US/prod/collateral/voicesw/ps6788/phones/ps379/ps8535/images/product_data_sheet0900aecd8069bb68-1.jpg

[ff] Goldviolin.com, 2009, "Freedom Phone," http://www.goldviolin.com/Amplified_Freedom_Phone_with_Caller_ID_p/90419.htm

5.1.20 (Sense Status, n/a) → (Function_add, Product)

Table 4 shows that a functional design change is needed for the sense status function as specified in this rule. This function typically does not involve user activity since the product senses the status within its system. This functional design change is one where functionality is added to the product, thus the function does not occur until added to the product. A product can be made more universal with a functional design change by adding the sense status function. As shown in Fig. 28, the more universal phone adds sense status functionality to sense an imported auditory status. This functionality addition allows the user to operate the phone without hand use, making the product more universal. This rule solely comes from the phone product pair study. In the product pair study, the function sense status always followed the function import status. This rule could be applied to any product where status sensing functionality can be added including auditory, tactile, olfactory, visual, and gustatory statuses.

5.1.21 (Import Hand, n/a) → (Function_add, Reaching)

Table 4 shows that a functional design change is needed for the import hand function done by the user activity of reaching as specified in this rule. This functional design change is one where functionality is added to the product, thus the function and user activity does not occur until they are added to the product. A product can be made more universal with a functional design change by adding the import hand function. As shown in Fig. 29, the more universal toilet adds import hand functionality to import the users hand to control the toilet seat lift controls. This functionality addition allows users with reduced functioning of their core and lower extremity to still have the freedom to sit and stand without assistance, making the product more universal. The user activity of reaching is added with the function as shown in the rule. This rule stems from the arm chair, recliner, toilet, and signage product pair studies. The more universal arm chair and recliner products add the import hand function to also control seat lifts whereas the more universal signage product adds the function to indicate a tactile status to the user with Braille. This rule could be applied to any product where hand use is not required but the import hand function can be added.

Fig. 29 The universal toilet (right) adds import hand functionality to operate seat lift controls allowing users to sit and stand without assistance, making it more universal than the typical toilet (left) [gg] [hh]

[gg] Contour-showers.co.uk, 2009, "Toilet Seat," http://www.contour-showers.co.uk/products/ancillary-items/toilet-seat
[hh] 4-lift-chairs.com, 2009, "Tush Push Toilet Seat Lift," http://www.4-lift-chairs.com/products/tush-push-toilet-seat-lift.html

5.1.22 (Position Hand, n/a) → (Function_add, Reaching)

Table 4 shows that a functional design change is needed for the position hand function done by the user activity of reaching as specified in this rule. This functional design change is one where functionality is added to the product, thus the function and user activity does not occur until they are added to the product. A product can be made more universal with a functional design change by adding the position hand function. As shown in Fig. 29, the more universal toilet adds position hand functionality to position the users hand to control the toilet seat lift controls. This functionality addition allows users with reduced functioning of their core and lower extremity to still have the freedom to sit and stand without assistance, making the product more universal. The user activity of reaching is added with the function as shown in the rule. This rule stems from the arm chair, recliner, toilet, and signage product pair studies. In the product pair studies, the function position hand always followed the function import hand. The more universal arm chair and recliner products add the position hand function to also control seat lifts whereas the more universal signage product adds the function to indicate a tactile status to the user with Braille. This rule could be applied to any product where hand use is not required but the position hand function can be added.

5.1.23 (Guide Solid, n/a) → (Function_add, Pushing)

Table 4 shows that a functional design change is needed for the guide solid function done by the user activity of pushing as specified in this rule. This functional design change is one where functionality is added to the product, thus the function and user activity does not occur until they are added to the product. A product can be made more universal with a functional design change by adding the guide solid function. As shown in Fig. 30, the more universal recliner adds guide solid functionality to push the seat lift control buttons. This functionality addition allows users with reduced functioning of their core and lower extremity to still have the freedom to sit and stand without assistance, making the product more universal. The user activity of pushing is added with the function as shown in the rule. This rule stems from the arm chair, recliner, and toilet product pair studies. The more universal arm chair and toilet products add the guide solid function to also control seat lifts. This rule could be applied to any product where the guide solid function can be added such as in pushing a button or switch.

Fig. 30 The seat lift control of the universal recliner (right) adds guide solid functionality to make the product more universal [ii] [jj]

[ii] Easyrecliner.com, 2009, "REC-516 Series Leather Recliner by Stanley Chair," http://easyrecliner.com/pro1175778.html

[jj] 1stseniorcare.com, 2009, "Golden Technologies Regal PR751TY Lift Recliner," http://www.1stseniorcare.com/goldentechnologiesregalpr751tyliftreclinerfreefrontdoordelivery.aspx

5.1.24 (Sense Hand, n/a) → (Function_add, Product)

Table 4 shows that a functional design change is needed for the sense hand function as specified in this rule. This function typically does not involve user activity since the product senses the hand within its system. This functional design change is one where functionality is added to the product, thus the function does not occur until added to the product. A product can be made more universal with a functional design change by adding the sense hand function. As shown in Fig. 20 on page 39, the more universal sink faucet adds hand sensing functionality to sense the user's hand. This functionality addition allows the user to operate the sink faucet without hand use, making the product more universal. This rule solely comes from the sink faucet product pair study. In the product pair study, the function sense status always followed the function position hand. This rule could be applied to any product where hand sensing functionality can be added such as motion sensing and hand recognition products.

5.1.25 (Guide Hand, n/a) → (Function_add, Manipulating)

Table 4 shows that a functional design change is needed for the guide hand function done by the user activity of manipulating as specified in this rule. This functional design change is one where functionality is added to the product, thus the function and user activity does not occur until they are added to the product. A product can be made more universal with a functional design change by adding the guide hand function. As shown in Fig. 24 on page 46, the more universal signage adds guide hand functionality to guide the user's hand to indicate the Braille status. This functionality addition allows users with seeing disabilities to communicate with signage, making the product more universal. The user activity of manipulating is added with the function as shown in the rule. This rule solely comes from the signage product pair study. This rule could be applied to any product where hand use is not required but the guide hand function can be added.

5.1.26 (Export Hand, n/a) → (Function_add, Pulling)

Table 4 shows that a functional design change is needed for the export hand function done by the user activity of pulling as specified in this rule. This functional design change is one where functionality is added to the product, thus the function and user activity does not occur until they are added to the product. A product can be made more universal with a functional design change by adding the export hand function. As shown in Fig. 24 on page 46, the more universal signage adds export hand functionality to export the user's hand after receiving the Braille status. This functionality addition allows users with seeing disabilities to communicate with signage, making the product more universal. The user activity of pulling is added with the function as shown in the rule. Pulling means the user pulls their hand towards the body to export their hand from the product system instead of releasing their hand from the product since the hand is not secured. This rule solely comes from the signage product pair study. The sink faucet product pair study shows the more universal design contains the export hand function by pulling user activity; however, this is a morphological design change from the typical product instead of added functionality. This rule could be applied to any product where hand use is not required but the import hand function has been added and the export hand function can be added.

5.1.27 (Import Electrical Energy, n/a) → (Function_add, Product)

Table 4 shows that a functional design change is needed for the import electrical energy function as specified in this rule. This function typically does not involve user activity since the product imports electrical energy to its system. This functional design change is one where functionality is added to the product, thus the function does not occur until added to the product. A product can be made more universal with a functional design change by adding the import electrical energy function. As shown in Fig. 31, the more universal car ingress system adds import electrical energy functionality to operate the gull-wing door. This functionality addition allows users in wheelchairs to enter the car with ease, making the product more universal. This rule stems from the arm chair, can opener, car ingress, recliner, and toilet product pair studies. In these product pair studies, the imported electrical energy automated at least one function. This rule could be applied to any product where import electrical energy functionality can be added to automate the product.

Fig. 31 Importing electrical energy as a functionality addition makes products more universal [kk] [ll]

5.1.28 (Transfer Electrical Energy, n/a) → (Function_add, Product)

Table 4 shows that a functional design change is needed for the transfer electrical energy function as specified in this rule. This function typically does not involve user activity since the product transfers electrical energy within its system. This functional design change is one where functionality is added to the product, thus the function does not occur until added to the product. A product can be made more universal with a functional design change by adding the transfer electrical energy function. As shown in Fig. 31, the more universal car ingress system adds transfer electrical energy functionality to operate the gull-wing door. This functionality addition allows users in wheelchairs to enter the car with ease, making the product more universal. This rule stems from the arm chair, can opener, car ingress, recliner, and toilet product pair studies. In these product pair studies, the function transfer electrical energy always

[kk] Edmunds.com, 2008, "2008 Chrysler PT Cruiser Consumer Review," http://www.edmunds.com/chrysler/ptcruiser/2008/consumerreview.html
[ll] Discountmobilityusa.com, 2009, "PT Cruiser Conversion," http://www.discountmobilityusa.com/logo/pt801.jpg

followed the function import electrical energy. This rule could be applied to any product where transfer electrical energy functionality can be added to automate the product.

5.1.29 (Convert Electrical Energy to Mechanical Energy, n/a)

→ (Function_add, Product)

Table 4 shows that a functional design change is needed for the convert electrical energy to mechanical energy function as specified in this rule. This function typically does not involve user activity since the product converts electrical energy to mechanical energy within its system. This functional design change is one where functionality is added to the product, thus the function does not occur until added to the product. A product can be made more universal with a functional design change by adding the convert electrical energy to mechanical energy function. As shown in Fig. 31, the more universal car ingress system adds convert electrical energy to mechanical energy functionality to operate the gull-wing door. This functionality addition allows users in wheelchairs to enter the car with ease, making the product more universal. This rule stems from the arm chair, can opener, car ingress, recliner, and toilet product pair studies. In these product pair studies, the function convert electrical energy to mechanical energy always followed the function transferred electrical energy. This rule could be applied to any product where converting electrical energy to mechanical energy functionality can be added to automate the product. This energy conversion is usually required to perform work.

6. APPLICATION

The rules presented in Section 5 are to be used as a guide by designers when in the conceptual design stage. To show the effectiveness of these rules they have been applied to typical consumer products to increase their accessibility. The typical products are selected from a non-interesting set aside from those used to create the association rules.

When creating an actionfunction diagram of a typical sports bottle similar to the one on the left of Fig. 32, a designer will see the product function separate solid done by the user activity of manipulating. WHO defines manipulating as “using fingers and hands to exert control over, direct or guide something”. This user activity is cumbersome for users with hand disabilities such as arthritis. The designer can make this sports bottle more universal by incorporating rule 5.1.12: (Separate Solid, Manipulating) → (Parametric, Pulling) into the design of the sports bottle top, as shown on the right of Fig. 32, which changes the user activity to pulling and eliminates find hand use. This flip-top design allows the user to operate the sports bottle with one hand and was ranked first out of thirty-two water bottle designs based on ease of use by the Good Housekeeping Research Institute [23].

Fig. 32 A parametric change makes the typical sports bottle (left) easier to open as shown in the more universal design (right) [mm] [nn]

The same actionfunction element of manipulating to separate solid is seen in the actionfunction diagram of a typical outlet plug design as shown on the left of Fig. 33. Again, using rule 5.1.12: (Separate Solid, Manipulating) → (Parametric, Pulling) to design a plug handle as shown on the right of Fig. 33, can make the outlet plug design more universal and eliminate the need for find hand use. More than Mobility, a mobility product supplier, states this plug design provides excellent leverage and can be removed with a reacher, a product that assists users in snagging out-of-reach items.

[mm] Everythingmugs.com, 2010, "Cycling Water Bottle (24 oz.)," http://www.everythingmugs.com/promotional-mugs/water-bottles/cycling-water-bottle-24-oz.html
[nn] Rei.com, 2010, "Nalgene OTG Bottle - 24 oz.," http://www.rei.com/product/729143

Fig. 33 Typical outlet plugs (left) can be cumbersome to remove; however, a parametric change can make removal easier [oo] [pp]

A typical bicycle allows the user to power oneself using only their lower extremity as shown in the left of Fig. 34. Integrating a morphological change as described in rule 5.1.14: (Convert Human Energy to Mechanical Energy, Pushing with Lower Extremity) → (Morphological, Pushing) can make the bicycle more universal. The AIM Full Body Bike, shown on the right of Fig. 34, was designed by Stanford University mechanical engineering students and provides users the option to pedal with their feet alone, their hands alone, or with their feet and hands simultaneously [66]. This design is more universal since users with lower extremity disabilities are still able to enjoy bike riding with the hand pedals.

[oo] Daddytypes.com, 2007, "Choke-Proofing Your Child-Proofing: Outlet Cover Edition," http://daddytypes.com/2007/02/13/choke-proofing_your_child-proofing_outlet_cover_edition.php
[pp] Morethanmobility.com, 2010, "Supagrip," http://www.morethanmobility.com/products/977

Fig. 34 Riding a bicycle using hand pedals (right) is morphologically different than a typical bicycle (left) and more universal [qq] [rr]

Corkscrews can often be burdensome and hard on the user's hands with repetitive forceful turning since their actionfunction diagram contains an element of turning the hand to guide a solid. Designers can make wine openers more universal by employing rules 5.1.18: (Guide Solid, Turning the Hand) → (Function_sub, n/a), 5.1.27: (Import Electrical Energy, n/a) → (Function_add, Product), 5.1.28: (Transfer Electrical Energy, n/a) → (Function_add, Product), and 5.1.29: (Convert Electrical Energy to Mechanical Energy, n/a) → (Function_add, Product). These rules eliminate the need to input human energy and turn the hand by automating the corkscrew as shown on the right of Fig. 35.

[qq] Reis, R., 2003, "AIM Full Body Bike," http://www.stanford.edu/group/AIM/AIMPrograms/BodyBike/Bike.html
[rr] Besportier.com, 2008, "Mission Bicycles," http://www.besportier.com/archives/mission-bicycles.html

Fig. 35 Automating a wine opener adds functionality with electrical energy and eliminates the need for turning the hand [ss] [tt]

[ss] Thekitchn.com, 2008, "How to Use a Waiter's Key Corkscrew," http://www.thekitchn.com/thekitchn/tips-techniques/how-to-use-a-waiters-key-corkscrew-055094
[tt] Luxuo.com, 2008, "Peugeot Electric Wine Opener," http://www.luxuo.com/gadgets/peugeot-electric-wine-opener.html

7. CONCLUSION

In conclusion, the universal design community lacks a set of rules to be used during conceptual design. Key barriers to implementing universal design include concern that adoption would require costly retooling of design teams, lack of knowledge, and an informal or decentralized product development process [3] and there exists a need for instruments that product developers can use to ensure their product can be used effectively by the widest range of potential user groups before it is mass produced [4].

The proposed universal design rules were developed after studying the relation between product function and user activity for fourteen typical and universal product pairs. Actionfunction diagrams relate product function to user activity and are the basis of study in this research. Parametric, morphological, and functional design changes were recorded as well as those actionfunction elements that remained the same when shifting from typical to universal actionfunction diagrams for each product pair. Each row of data in the dataset, or itemset, contained four items: product function, design change, typical product user activity, and the more universal product user activity. Finally, the Apriori algorithm was applied to these itemsets to extract interesting association rules. The order of items in the itemsets is not important; however, it is critical the item order is consistent among all itemsets.

The Apriori algorithm produced 1,023 association rules with input parameters of 70% minimum confidence and 0.5% minimum support levels. These rules were down-selected based on the prescribed rule format of: (Function, Typical User Activity) → (Change, Universal User Activity). In other words, for a given product function and user activity, the rules suggest a design change and new user activity for a more universal product. This rule format was chosen based on intuition. Also, product designers only know product function and user activity at the conceptual design level and would like to know design changes and new user activities to make their product more universal.

It is shown that no product changes are needed for functions of importing and exporting materials or control signals to and from the product in order to make it more universal. This is intuitive since these types of functions must occur for the product, typical or universal, to be functional. The rules suggesting no needed design change for a particular user activity and function may seem useless; however, there are two sides to these rules. No design change rules confirm our intuition and also prevent inefficient design efforts. A parametric design change is suggested for actionfunction elements involving find hand use to manipulate a product. A parametric design change eliminates the need for fine hand use and transforms the user activity to a lower effort action. Morphological design changes are proposed to solve actionfunction elements in a slightly more complex manner without adding or subtracting overall functionality. For example, converting human energy to mechanical energy with the upper body opposed to the lower body or actuating fluid flow with motion sensors instead of manual knobs. The majority of the recommended functional changes involve automating a product to make it more universal which might not be apparently obvious to designers during conceptual design.

The presented universal design rules correspond well with the seven principles of universal design [7]. Rule 5.1.12, (Separate Solid, Manipulating) → (Parametric, Pulling), suggests a parametric change to eliminate find hand use and provide users with low physical effort. Rule 5.1.14, (Convert Human Energy to Mechanical Energy, Pushing with Lower Extremity) → (Morphological, Pushing), suggests a morphological change to add a means of energy conversion via upper extremity user activity and provide users with flexibility in use. Rule 5.1.13, (Indicate Status, Communicate with Written Messages) → (Morphological, Communicate with Written Messages), suggests a morphological change to add a means of status indication and provide users with perceptible information. A rule suggesting a functional change to automate a product provide users with equitable use, simple and intuitive use, size and space for approach and use, and tolerance for error as the product performs most of the original user activities such as in the electric can opener product example.

Future work is needed to improve the use of universal design rules based on association rule-based learning. Studying more product pairs to increase the size and frequency of certain itemsets will alter the outcome of the Apriori algorithm producing more interesting rules. Also, studying actionfunction chains and the relation of preceding and subsequent elements may produce more interesting results designers can find useful. Such a study would require a change to itemset entries in the dataset and may involve rules of the form (Function A, Function B, Function C) → (Change), for example. A rule with this format would suggest a design change based on the sequence of product functions as observed in a product pair study.

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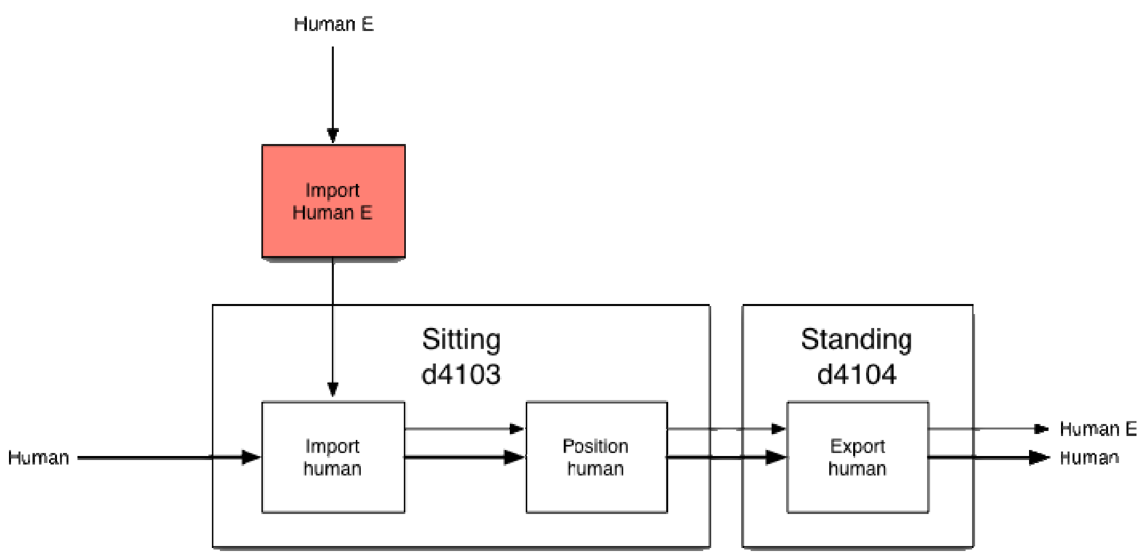
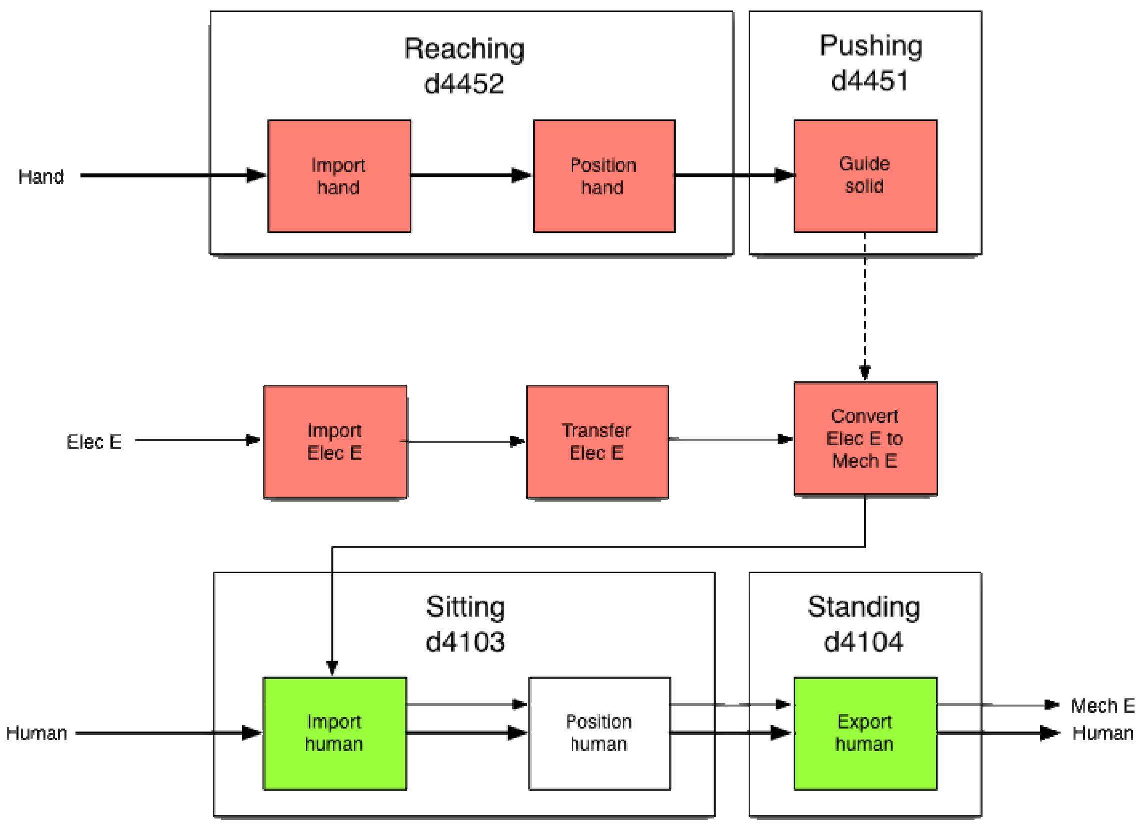
APPENDIX A

CONSUMER PRODUCTS WITH ACTIONFUNCTION DIAGRAMS

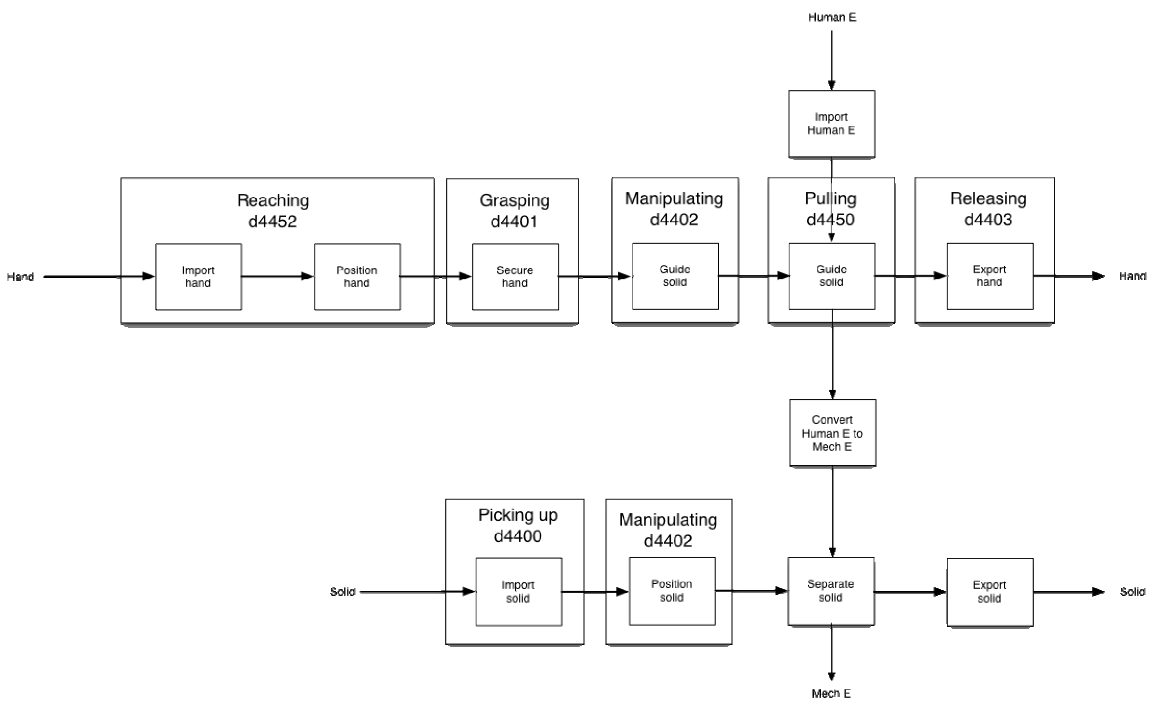
A.1 Typical Arm Chair



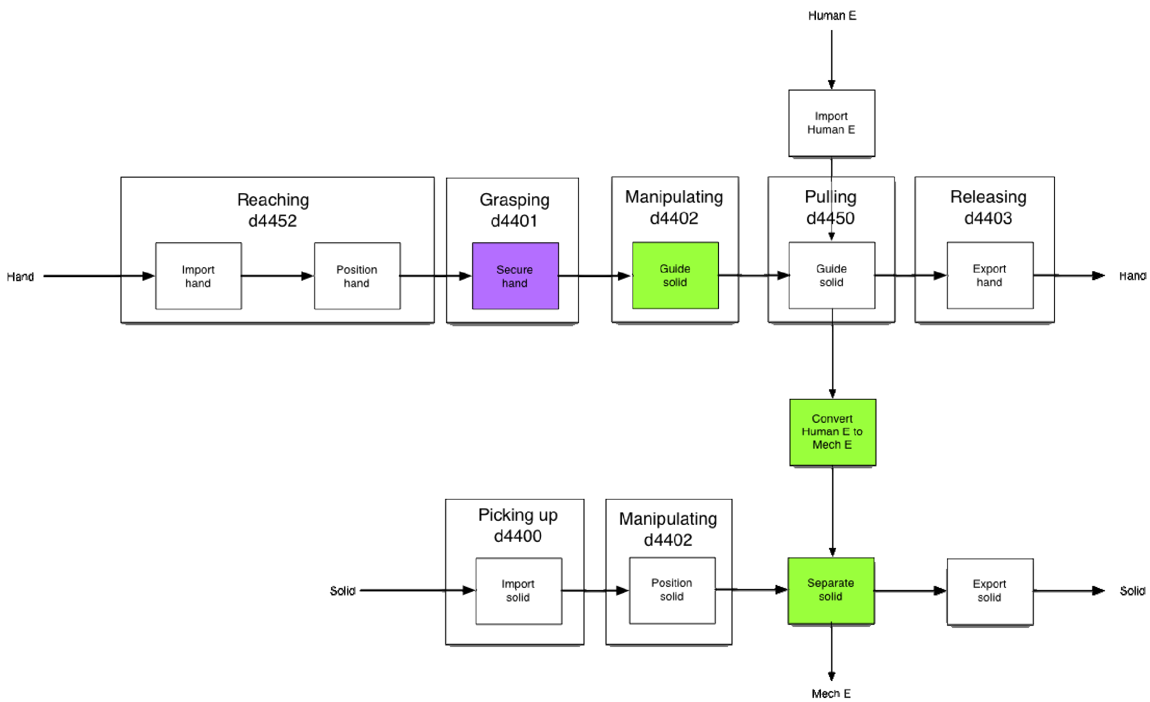
A.2 Universal Arm Chair



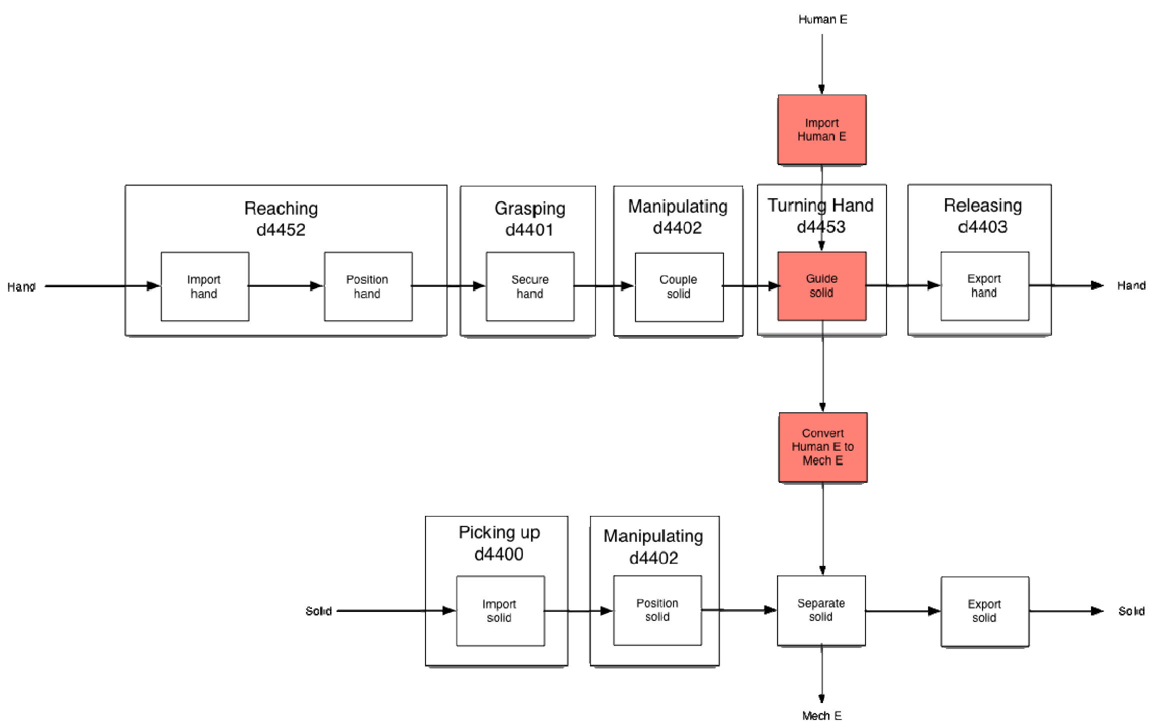
A.3 Typical Box Cutter



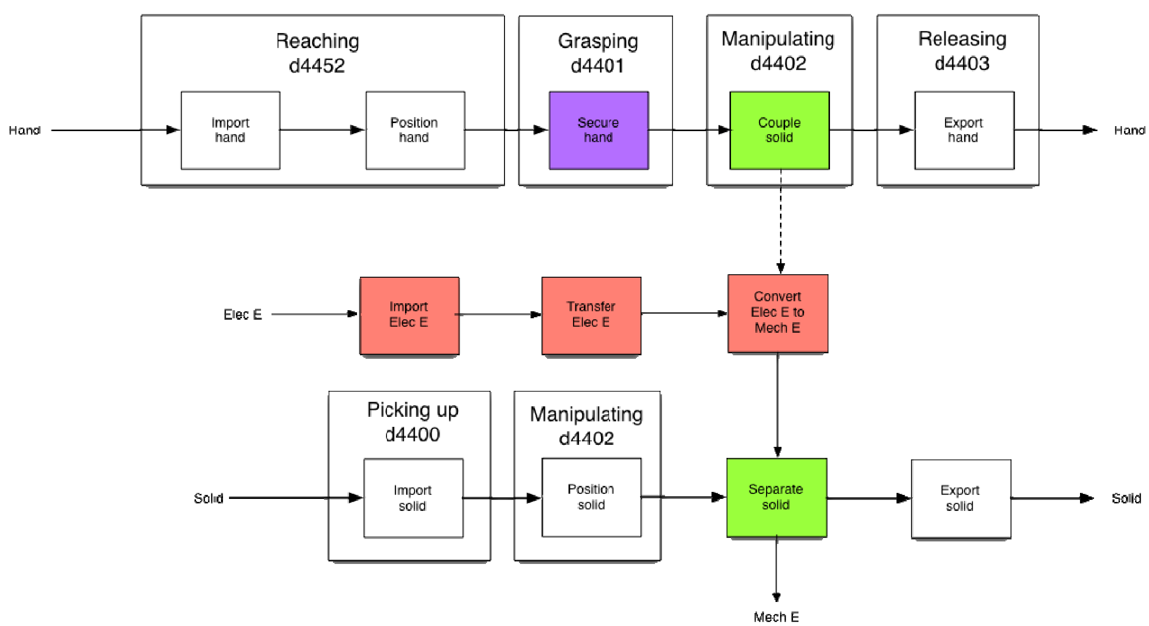
A.4 Universal Box Cutter



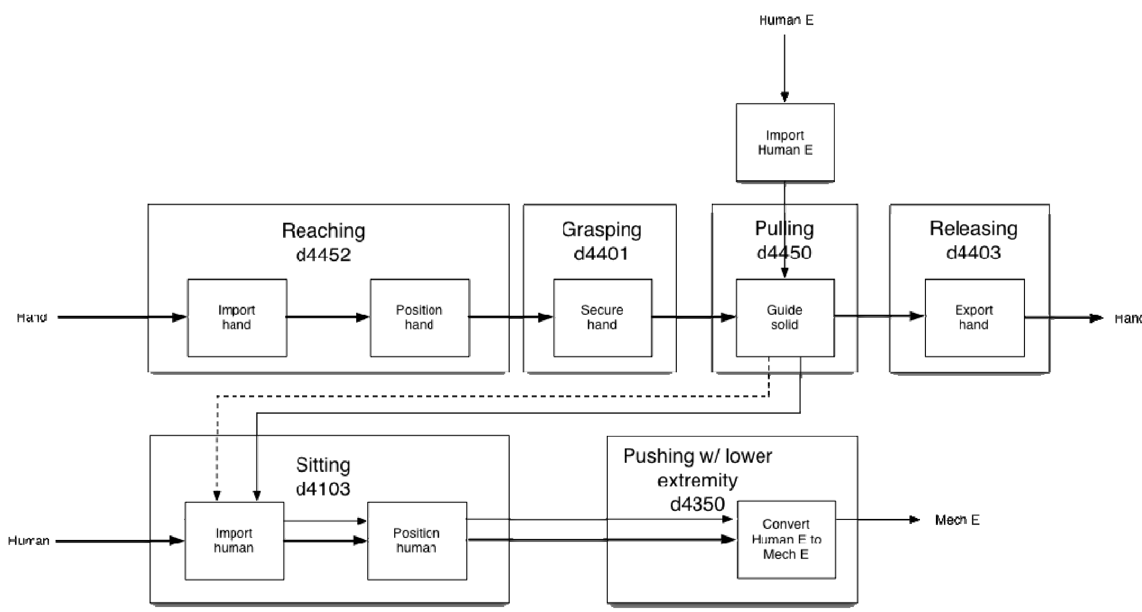
A.5 Typical Can Opener



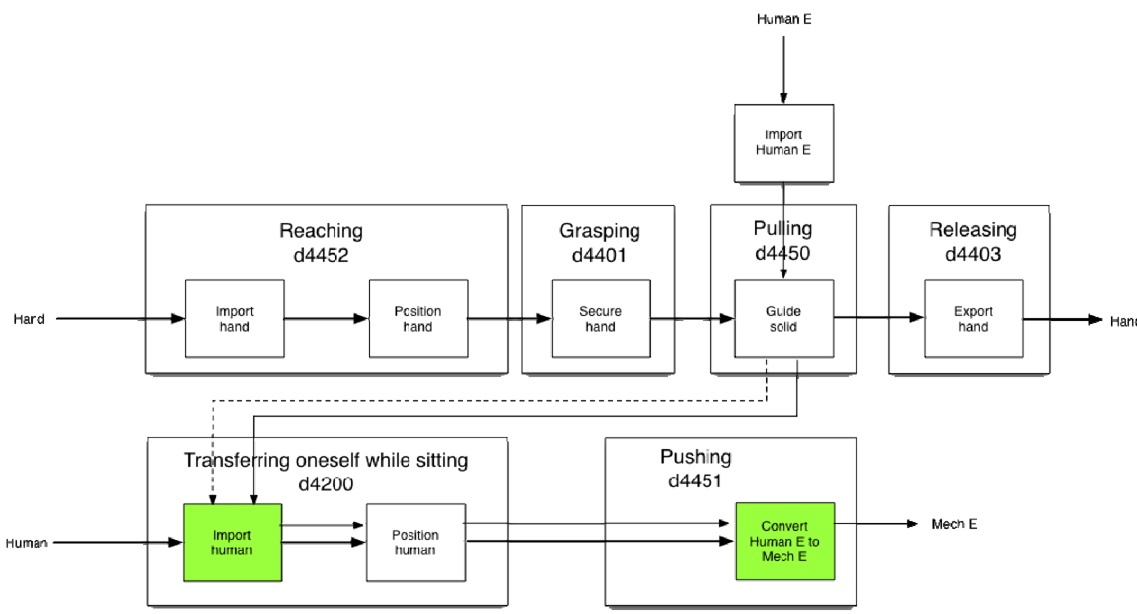
A.6 Universal Can Opener



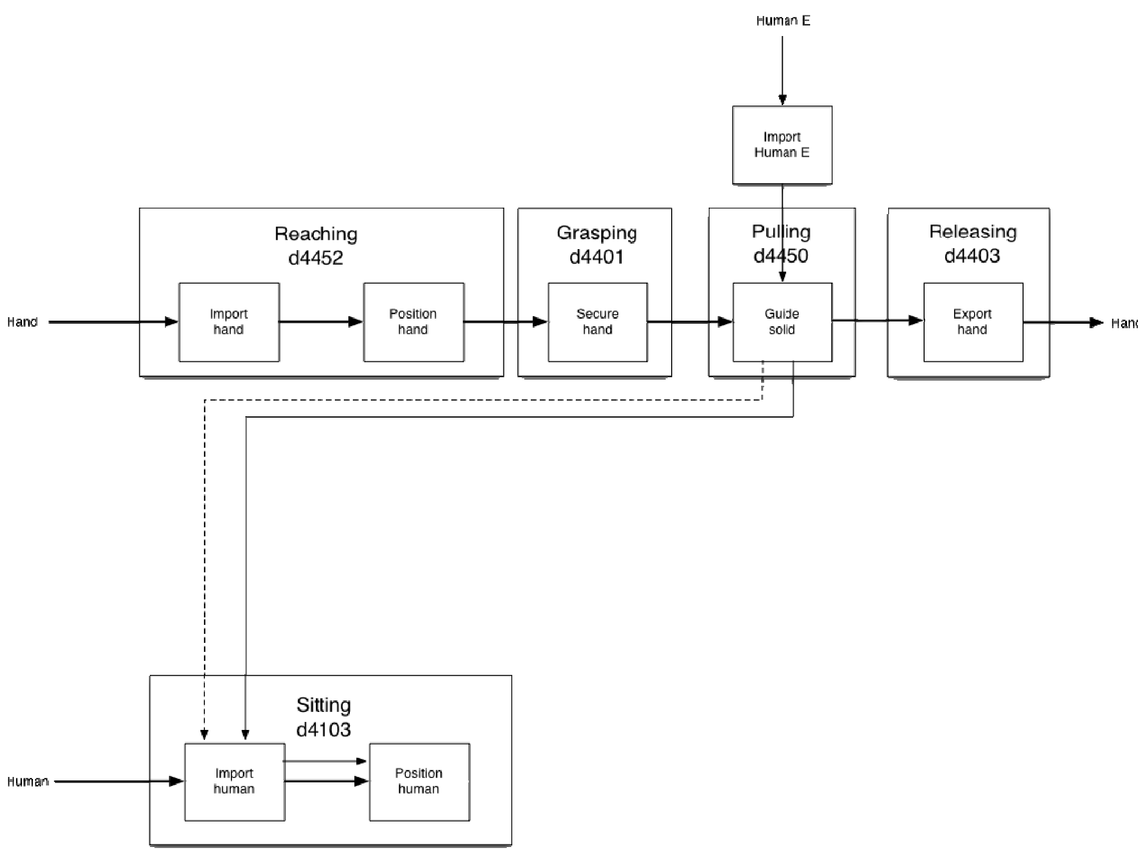
A.7 Typical Car Operation



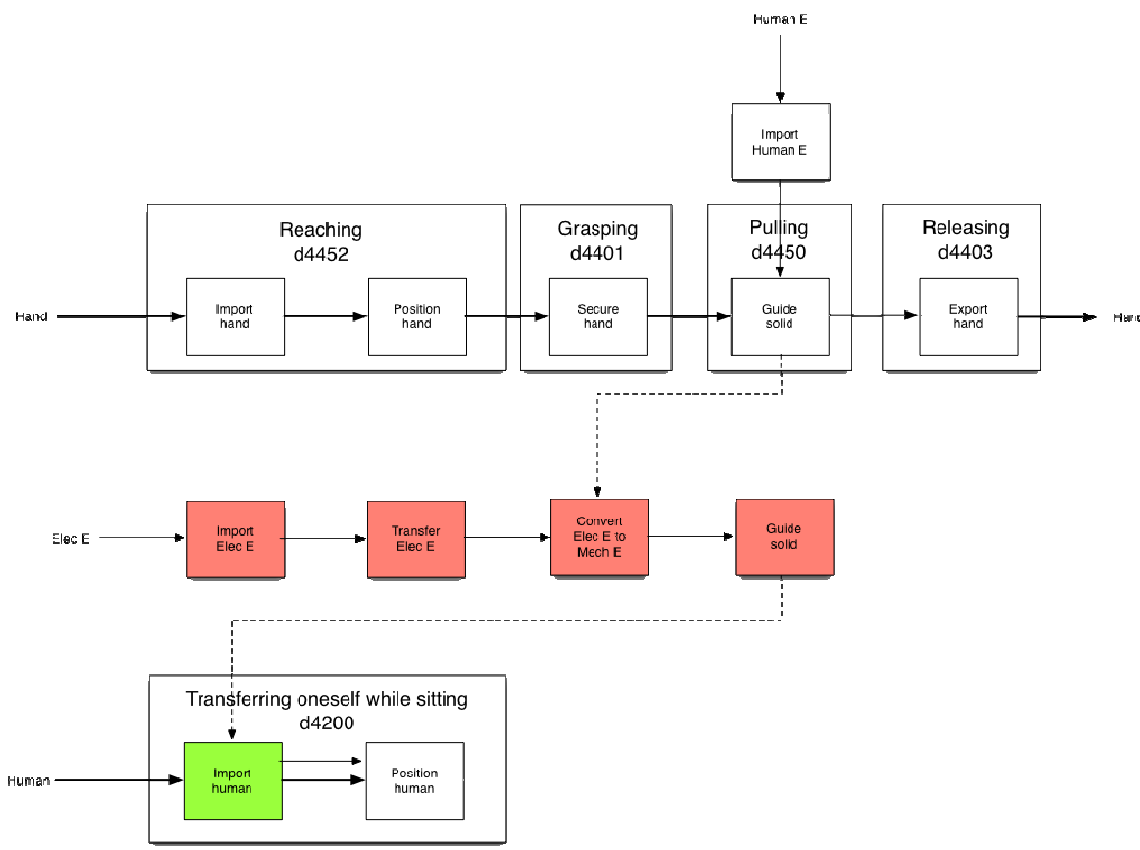
A.8 Universal Car Operation



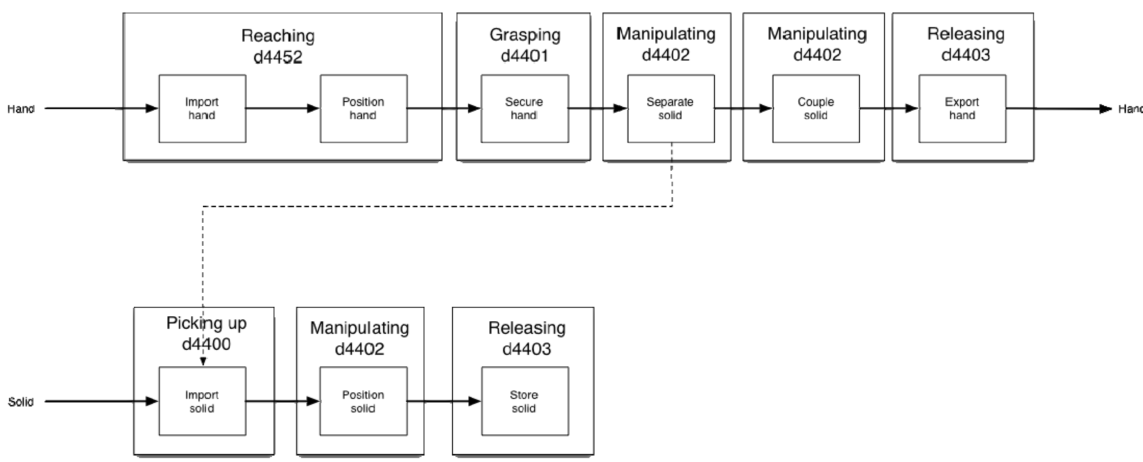
A.9 Typical Car Ingress



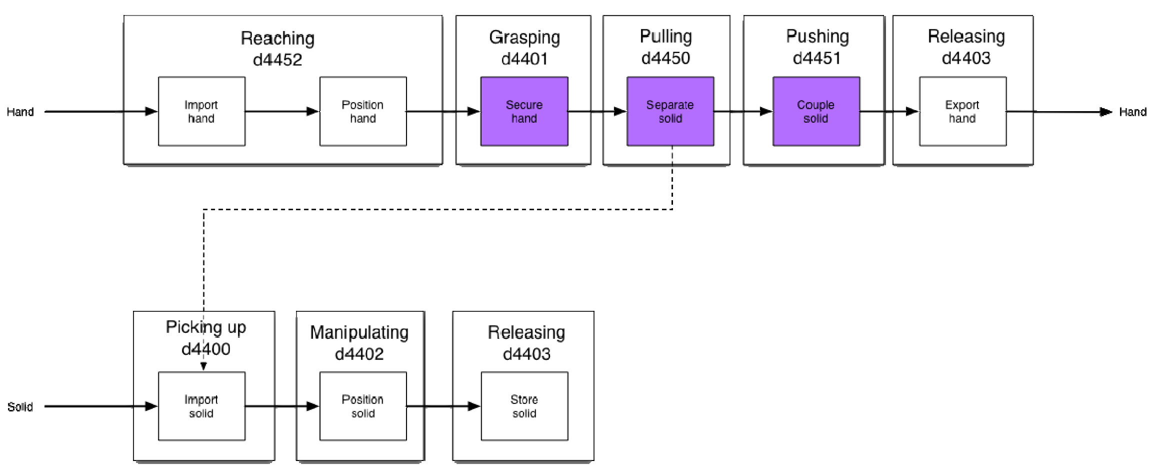
A.10 Universal Car Ingress



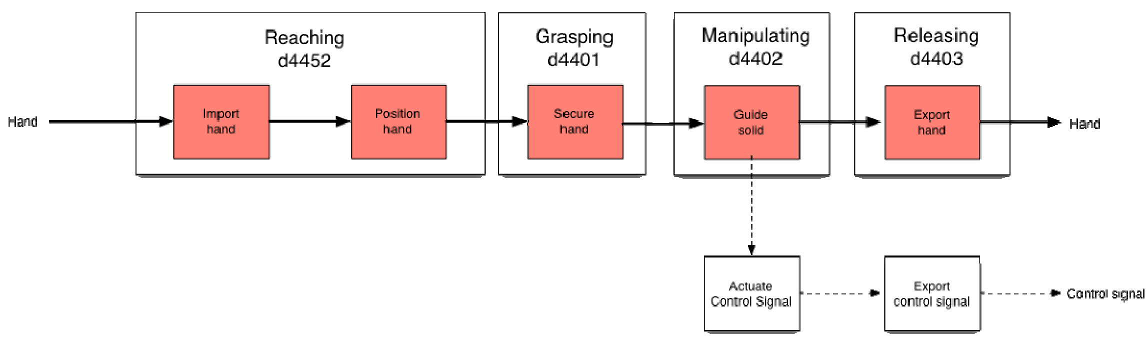
A.11 Typical Food Container



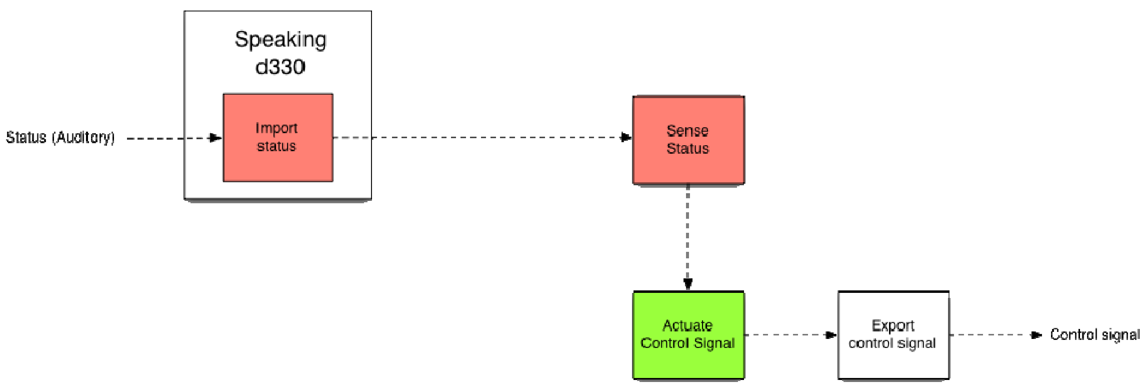
A.12 Universal Food Container



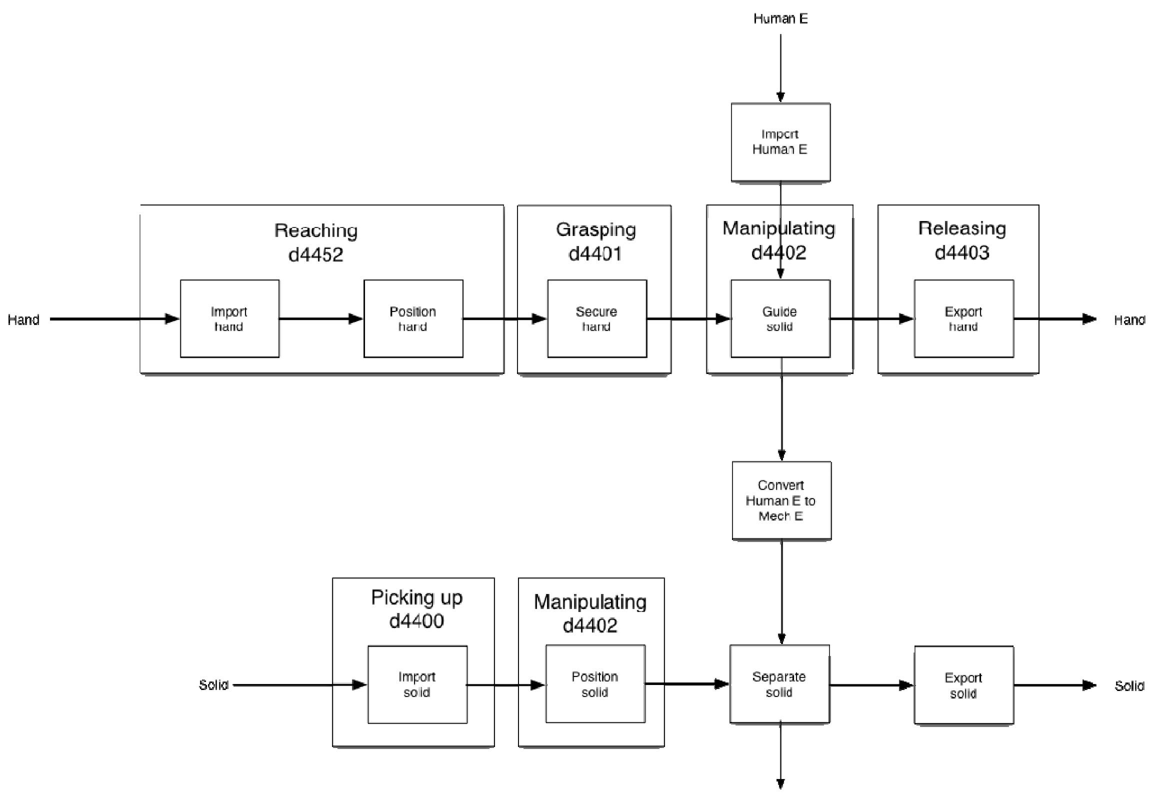
A.13 Typical Phone



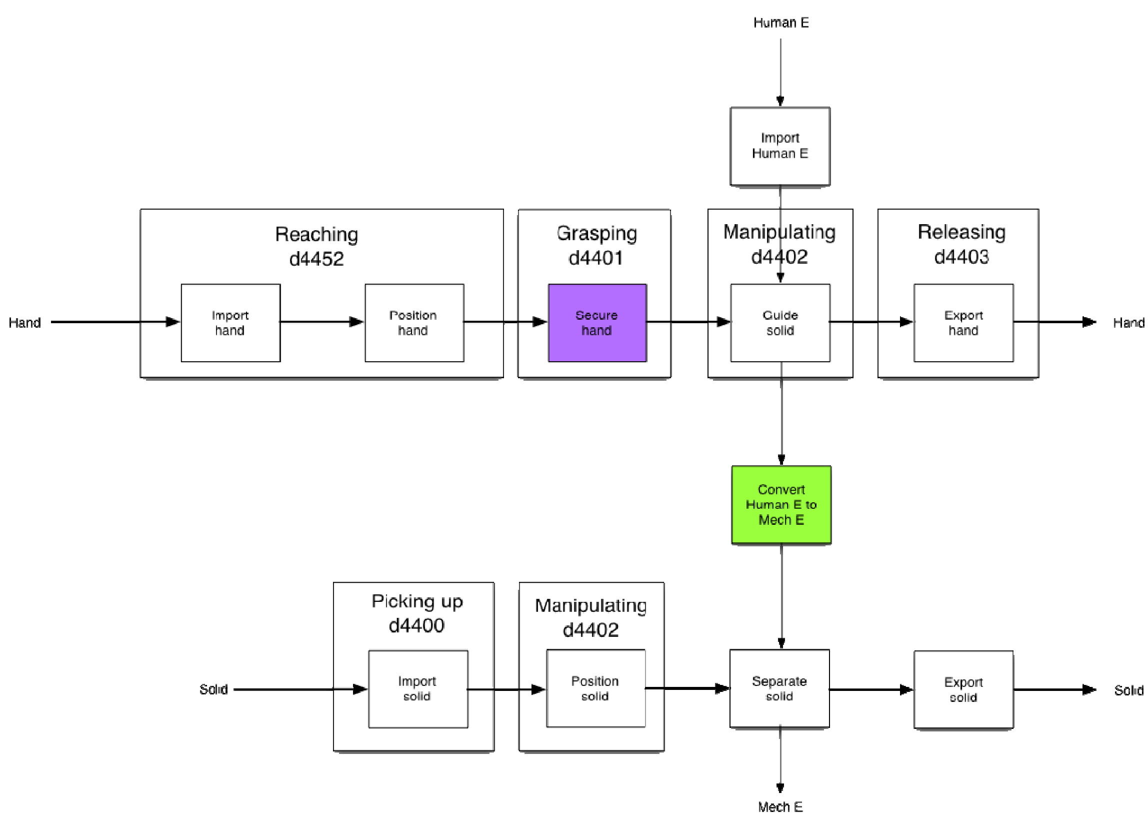
A.14 Universal Phone



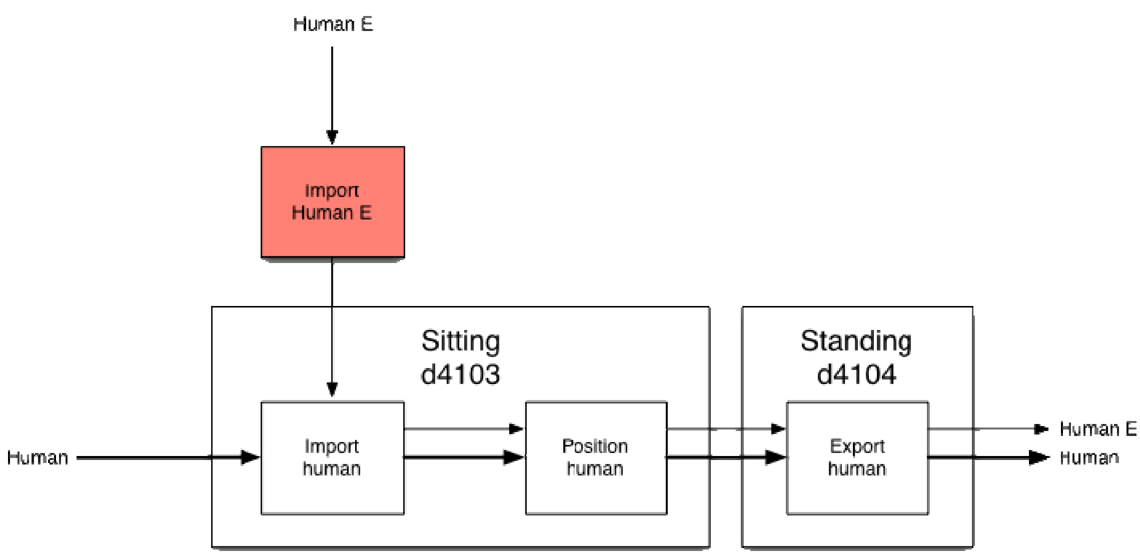
A.15 Typical Pruner



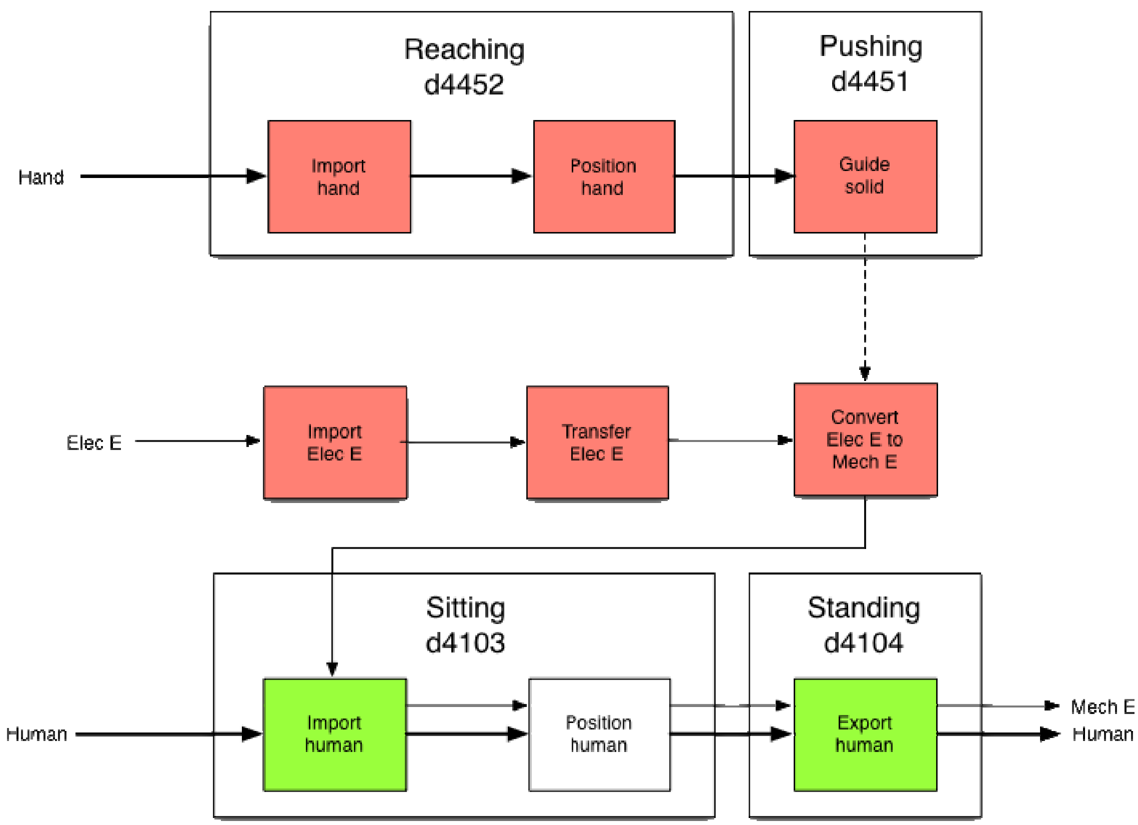
A.16 Universal Pruner



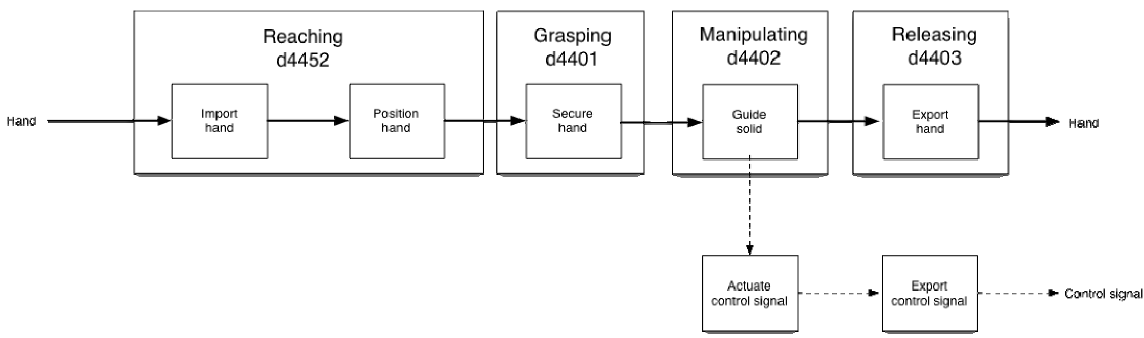
A.17 Typical Recliner



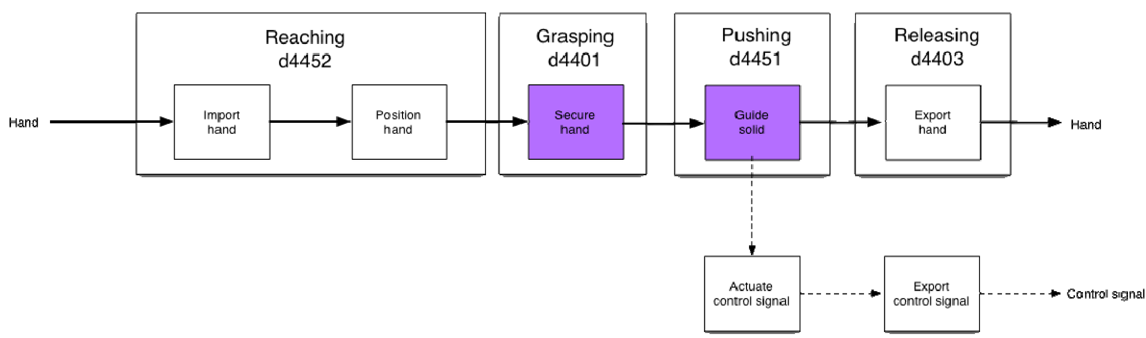
A.18 Universal Recliner



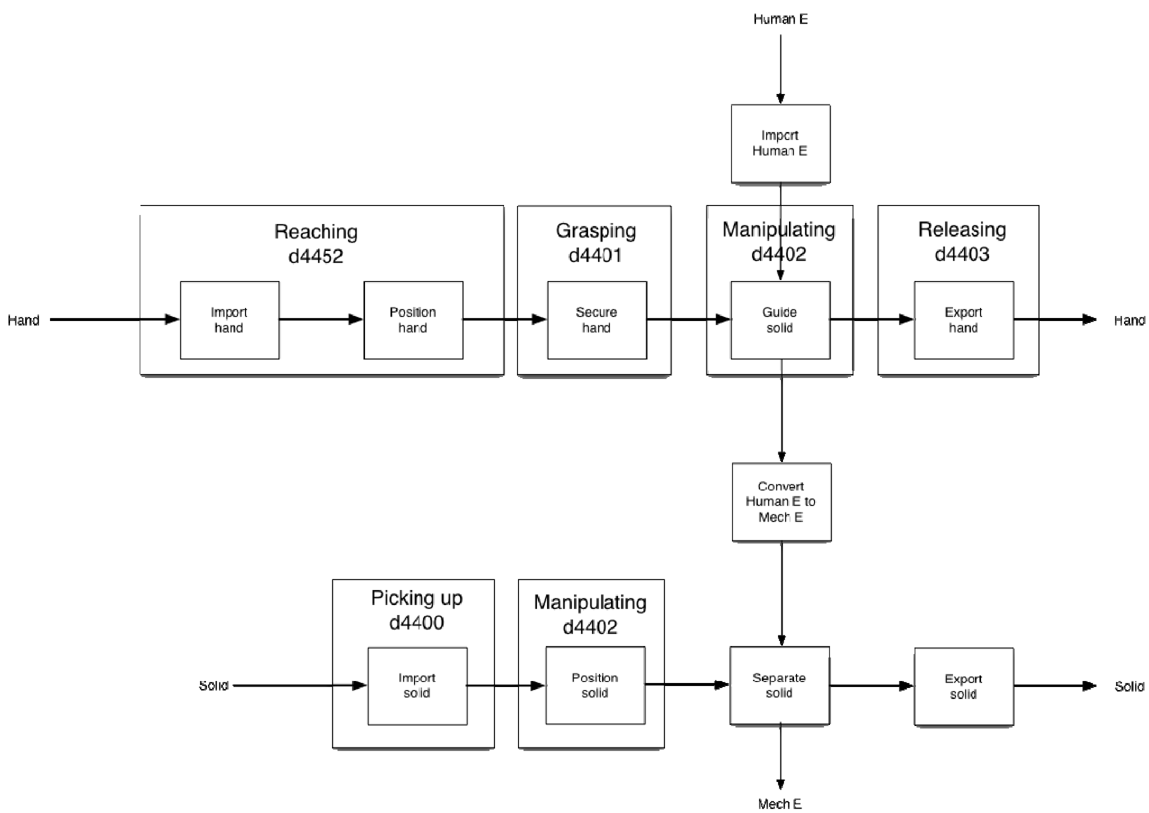
A.19 Typical Remote



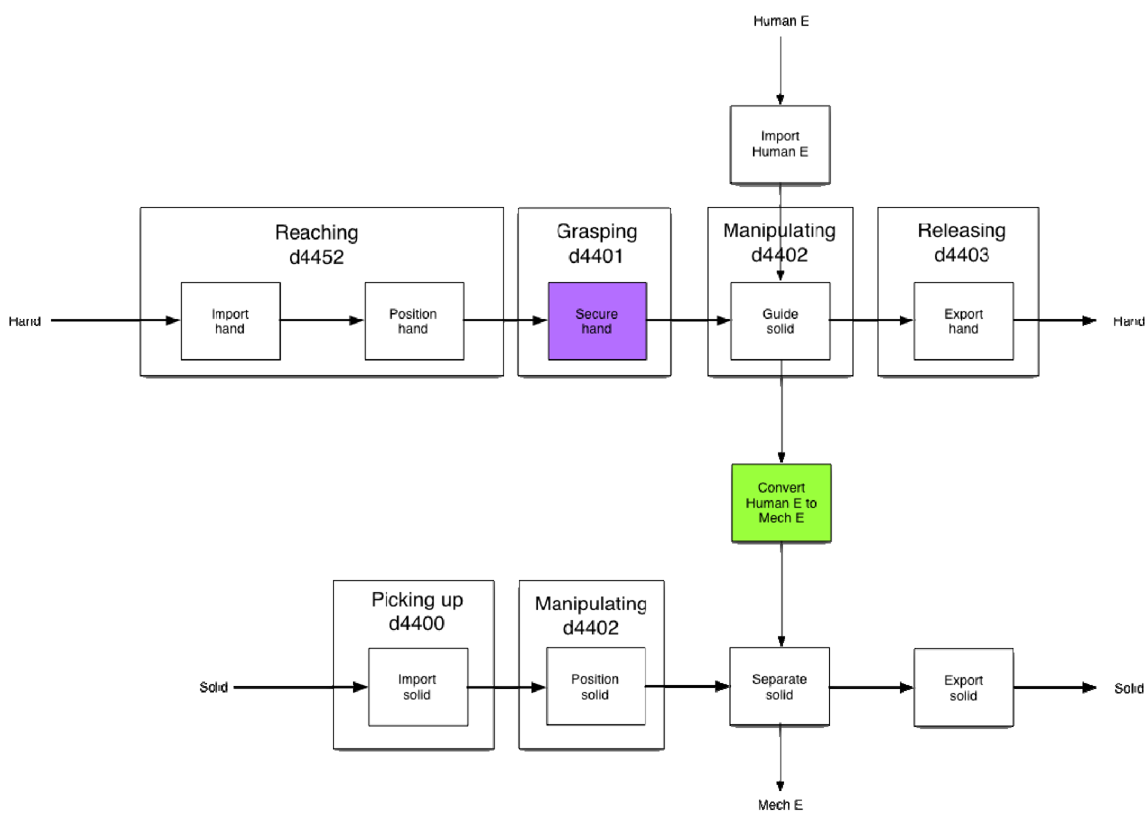
A.20 Universal Remote



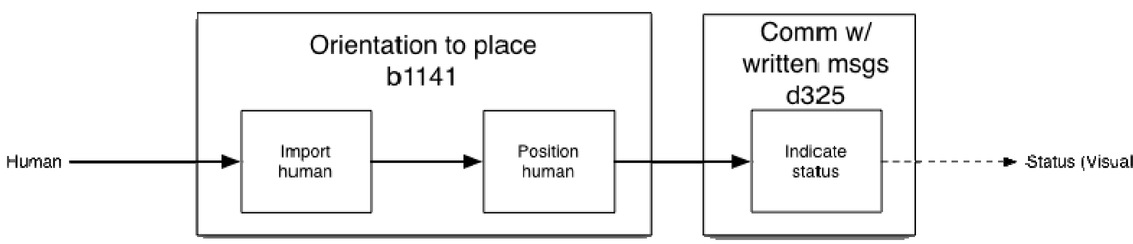
A.21 Typical Scissor



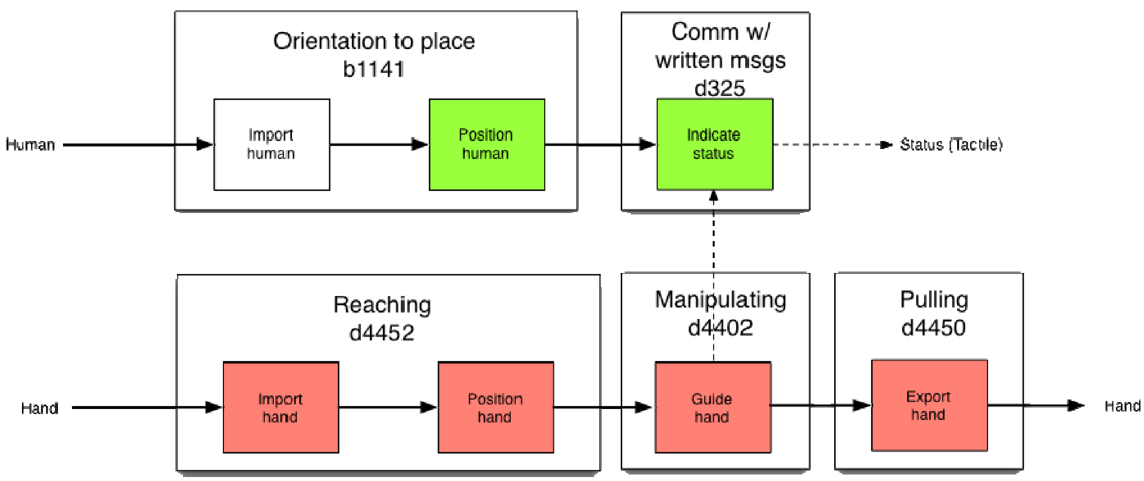
A.22 Universal Scissor



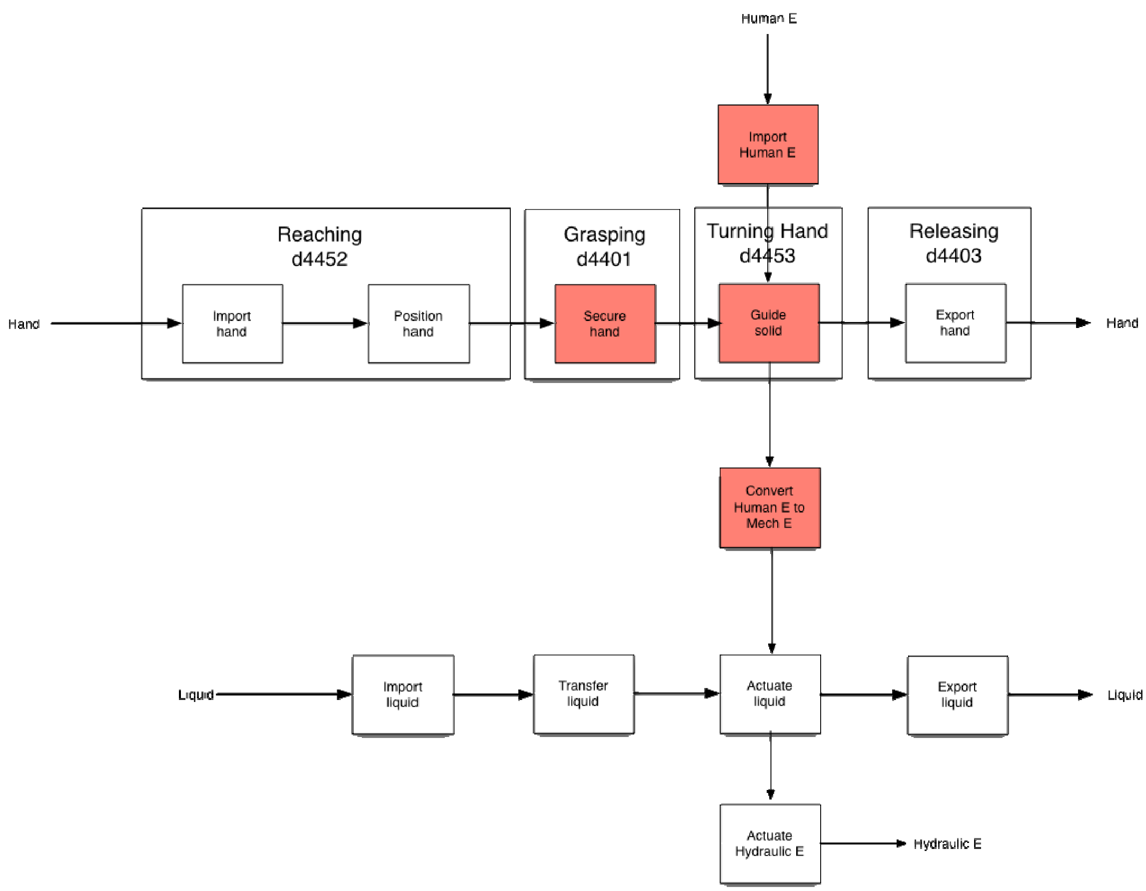
A.23 Typical Signage



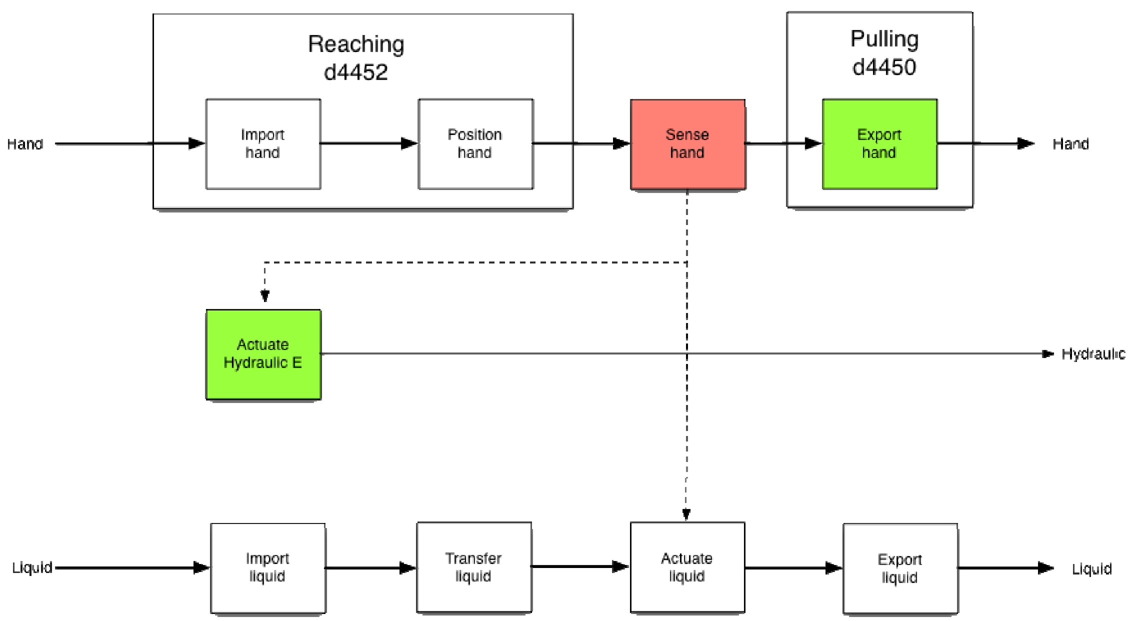
A.24 Universal Signage



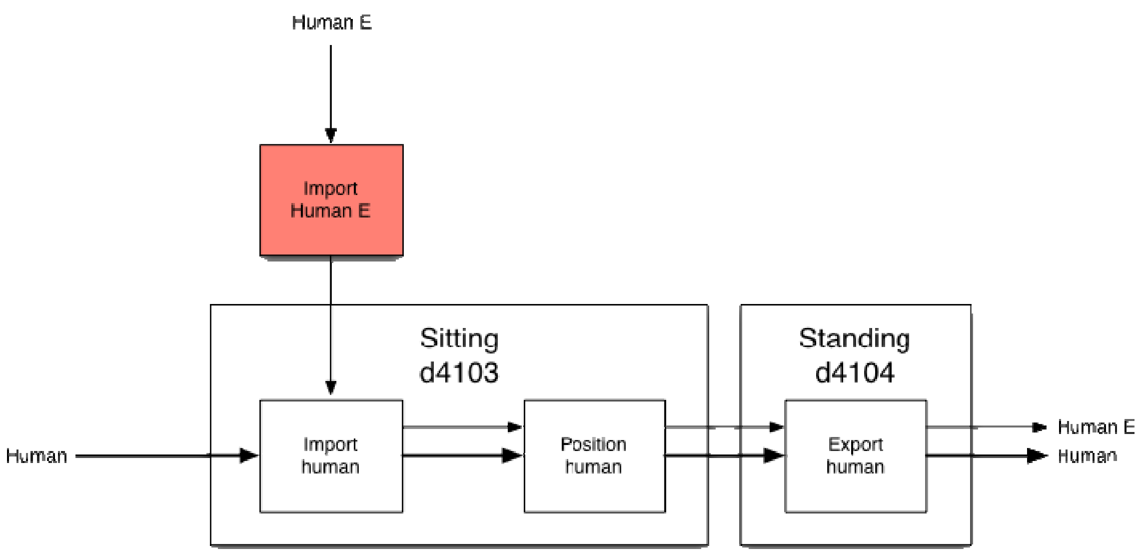
A.25 Typical Sink Faucet



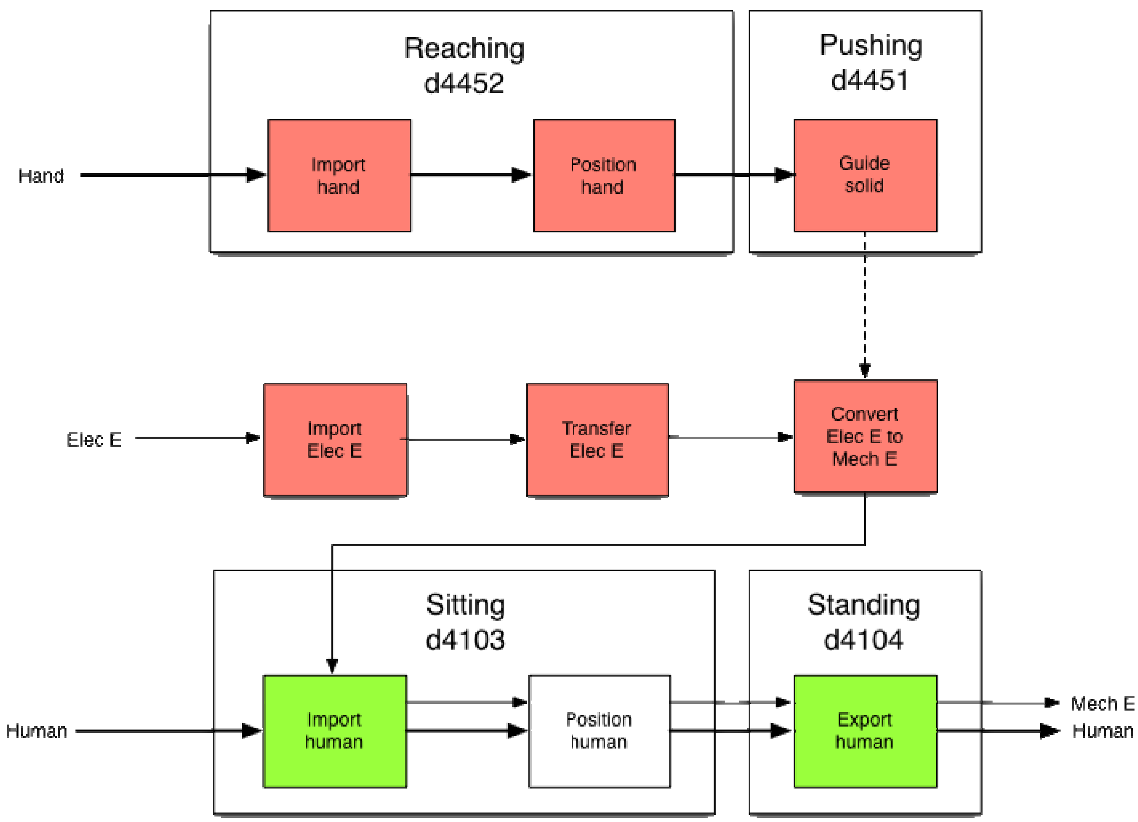
A.26 Universal Sink Faucet



A.27 Typical Toilet



A.28 Universal Toilet



APPENDIX B

ICF TERMINOLOGY DEFINITIONS

b1141 Orientation to place
Mental functions that produce awareness of one's location, such as one's immediate surroundings, one's town or country.

d325 Communicating with - receiving - written messages
Comprehending the literal and implied meanings of messages that are conveyed through written language (including Braille), such as following political events in the daily newspaper or understanding the intent of religious scripture.

d330 Speaking
Producing words, phrases and longer passages in spoken messages with literal and implied meaning, such as expressing a fact or telling a story in oral language.

d4103 Sitting
Getting into and out of a seated position and changing body position from sitting down to any other position, such as standing up or lying down.
Inclusions: getting into a sitting position with bent legs or cross-legged; getting into a sitting position with feet supported or unsupported

d4104 Standing
Getting into and out of a standing position or changing body position from standing to any other position, such as lying down or sitting down.

d4200 Transferring oneself while sitting
Moving from a sitting position on one seat to another seat on the same or a different level, such as moving from a chair to a bed.
Inclusions: moving from a chair to another seat, such as a toilet seat; moving from a wheelchair to a car seat
*Exclusion: changing basic body position (**d410**)*

d4350 Pushing with lower extremities
Using the legs and feet to exert a force on an object to move it away, such as pushing a chair away with a foot.

d4400 Picking up
Lifting or taking up a small object with hands and fingers, such as when picking up a pencil.

d4401 Grasping
Using one or both hands to seize and hold something, such as when grasping a tool or a door knob.

d4402 Manipulating
Using fingers and hands to exert control over, direct or guide something, such as when handling coins or other small objects.

d4403 Releasing
Using fingers and hands to let go or set free something so that it falls or changes position, such as when dropping an item of clothing.

d4450 Pulling
Using fingers, hands and arms to bring an object towards oneself, or to move it from place to place, such as when pulling a door closed.

d4451 Pushing
Using fingers, hands and arms to move something from oneself, or to move it from place to place, such as when pushing an animal away.

d4452 Reaching
Using the hands and arms to extend outwards and touch and grasp something, such as when reaching across a table or desk for a book.

d4453 Turning or twisting the hands or arms
Using fingers, hands and arms to rotate, turn or bend an object, such as is required to use tools or utensils.

VITA

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